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Technology Administration, U.S. Department of Commerce

Determination of the Planck constant at the National Institute of Standards and Technology

D. Haddad, F. Seifert, L.S. Chao, D.B. Newell, R. Liu, R.L. Steiner, J.R. Pratt, S. Schlamminger

National Institute of Standards and Technology

Outline

- The principle of the watt balance
- The apparatus, NIST-3
- The 2012/2013 measurement campaign
- Corrigendum and Addendum
- Outlook

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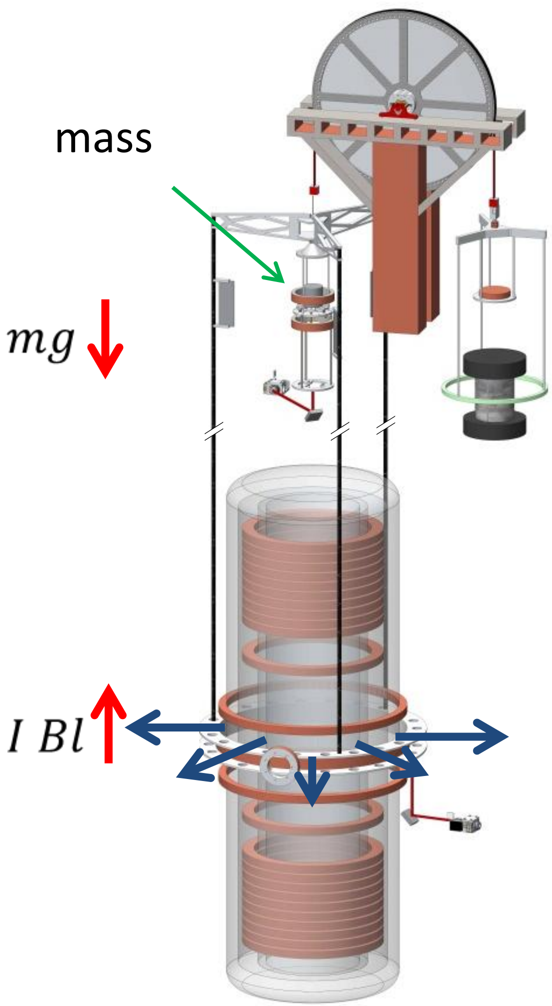
Principle of the watt balance in one slide

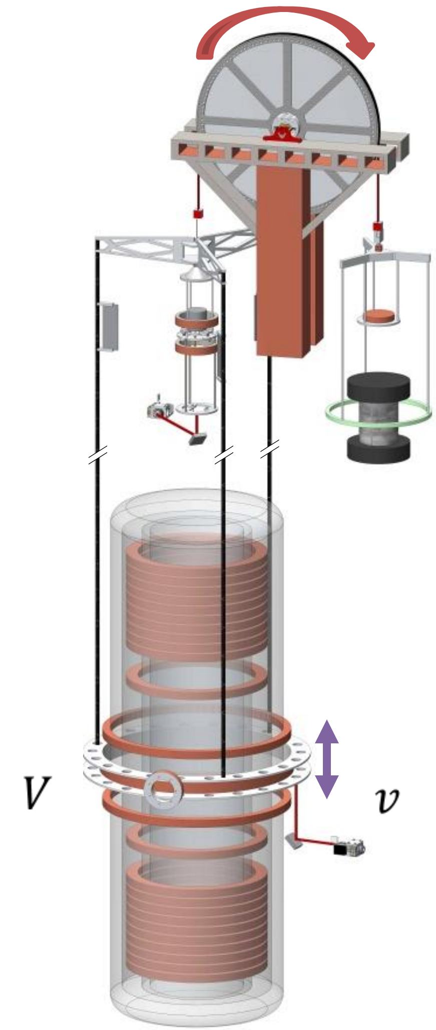
Force mode

$$mg = I\,Bl$$



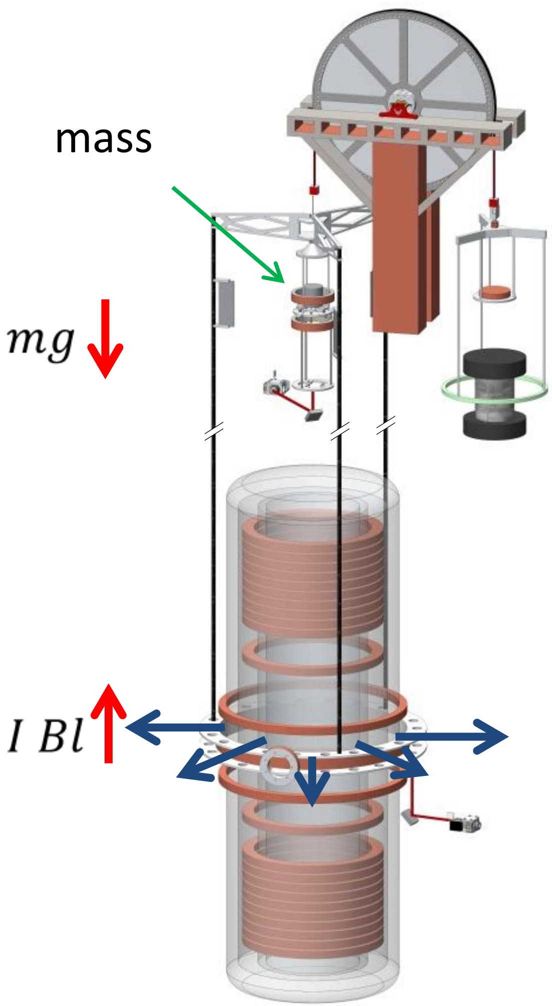
Velocity mode

$$V = v\,Bl$$



Principle of the watt balance in one slide

Force mode

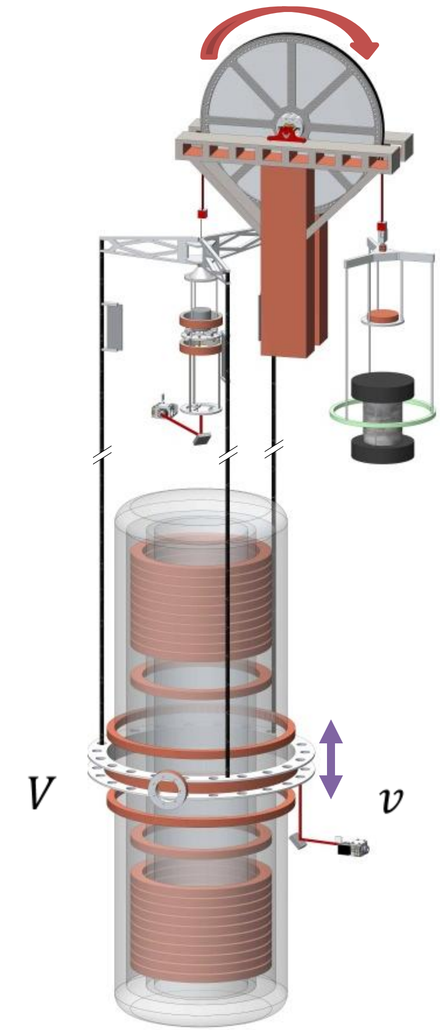


$$mg = I\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

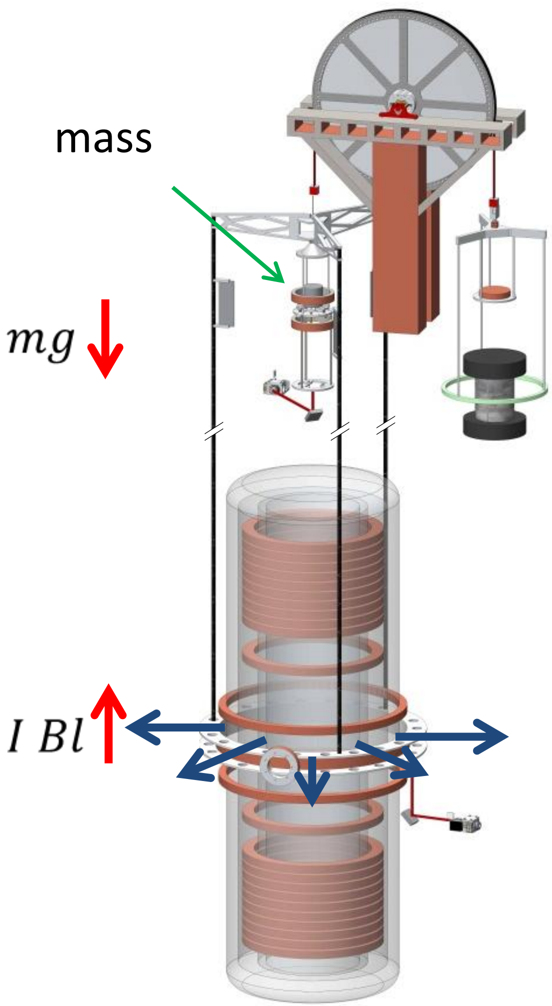
$$V = v\,Bl$$

Velocity mode



Principle of the watt balance in one slide

Force mode



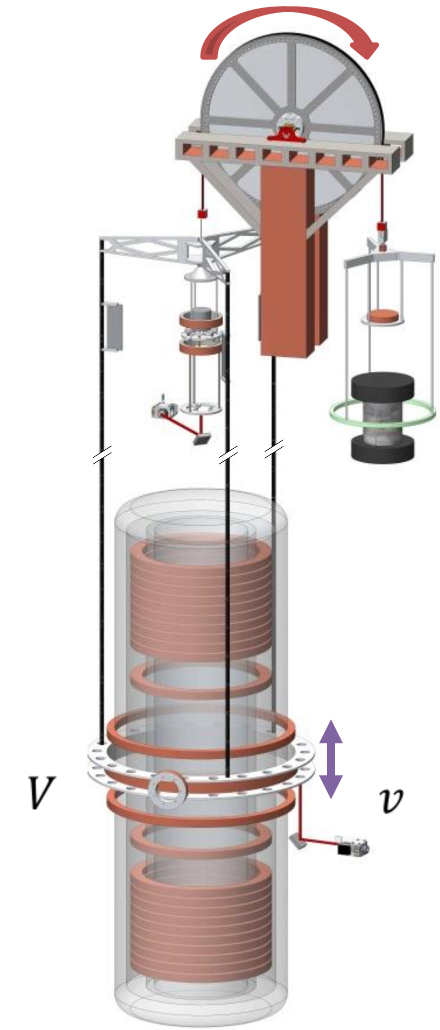
$$mg = I\,Bl$$

$$V = v\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

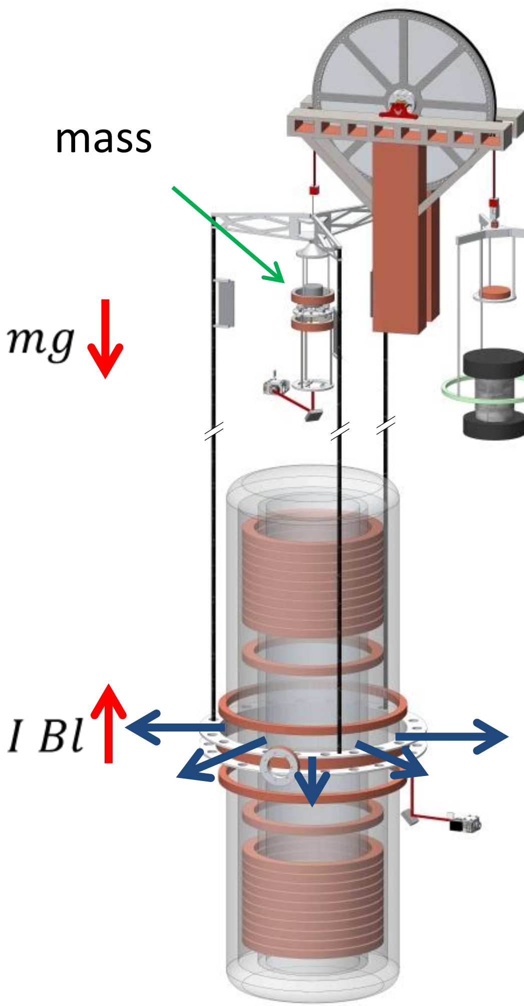
$$mgv = VI$$

Velocity mode



Principle of the watt balance in one slide

Force mode



$$mg = I\,Bl$$

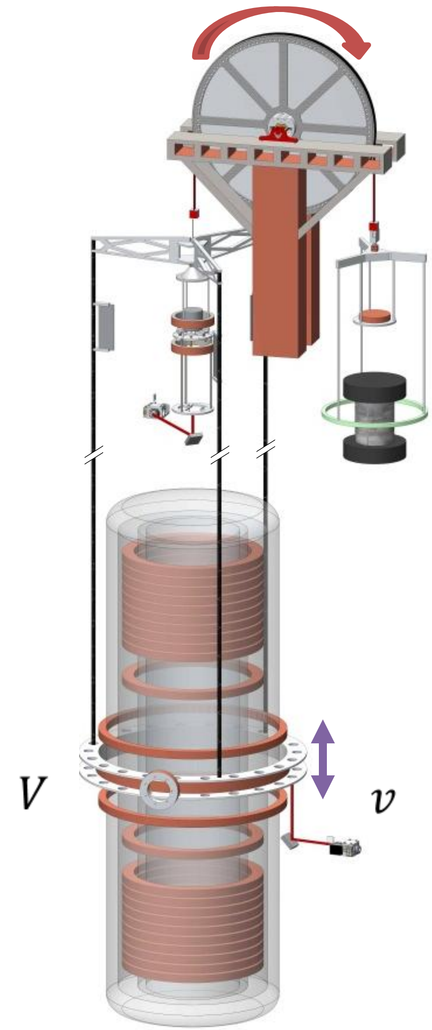
$$V = v\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

$$mgv = VI$$

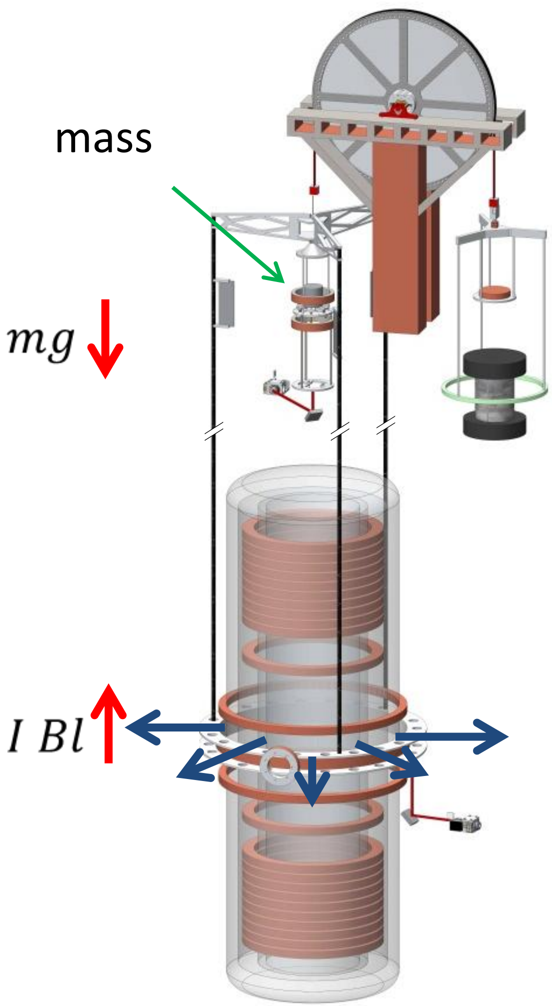
$$mgv = V_1 \frac{V_2}{R}$$

Velocity mode



Principle of the watt balance in one slide

Force mode



$$mg = I\,Bl$$

$$V = v\,Bl$$

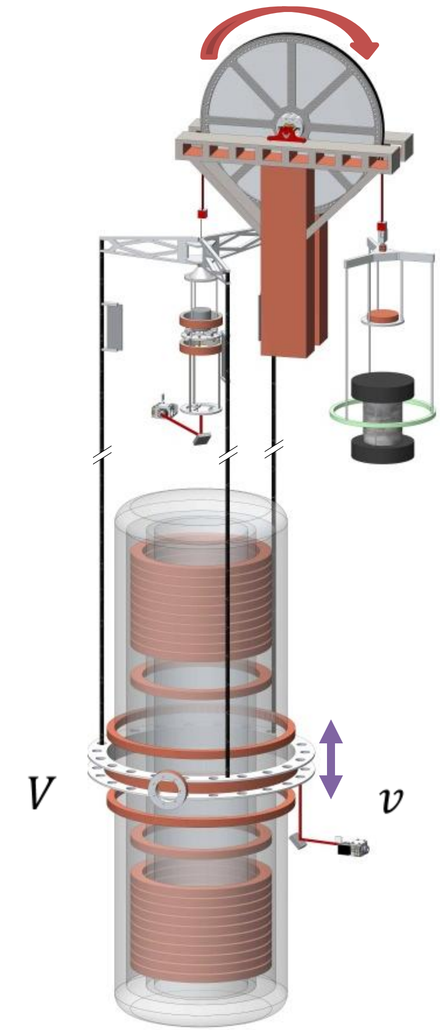
$$\frac{mg}{V} = \frac{I}{v}$$

$$mgv = VI$$

$$mgv = V_1 \frac{V_2}{R}$$

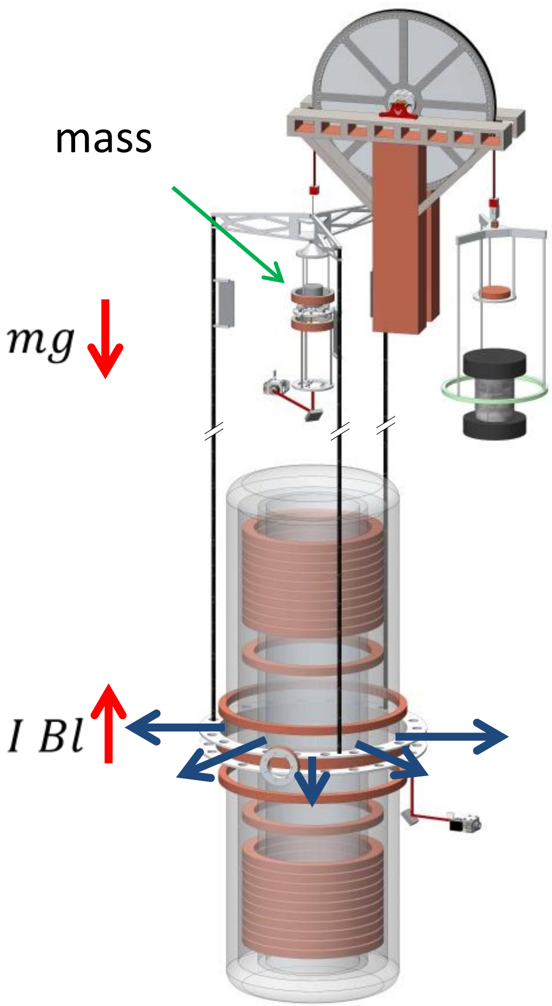
$$mgv = n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e} \frac{1}{r} \frac{e^2}{h}$$

Velocity mode

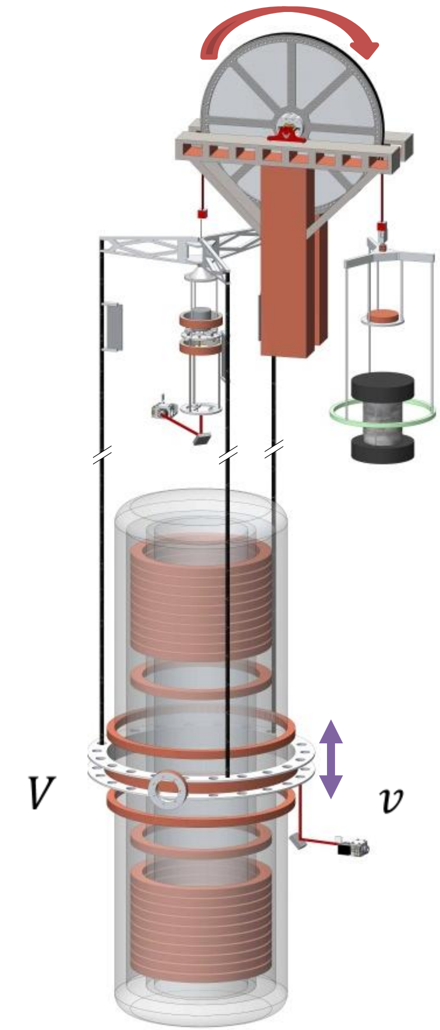


Principle of the watt balance in one slide

Force mode



Velocity mode



$$mg = I\,Bl \qquad V = v\,Bl$$

$$\frac{mg}{V} = \frac{I}{v}$$

$$mgv = VI$$

$$mgv = V_1 \frac{V_2}{R}$$

$$mgv = n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e} \frac{1}{r} \frac{e^2}{h}$$

$$mgv = \frac{n_1 n_2}{4r} f_1 f_2 h$$

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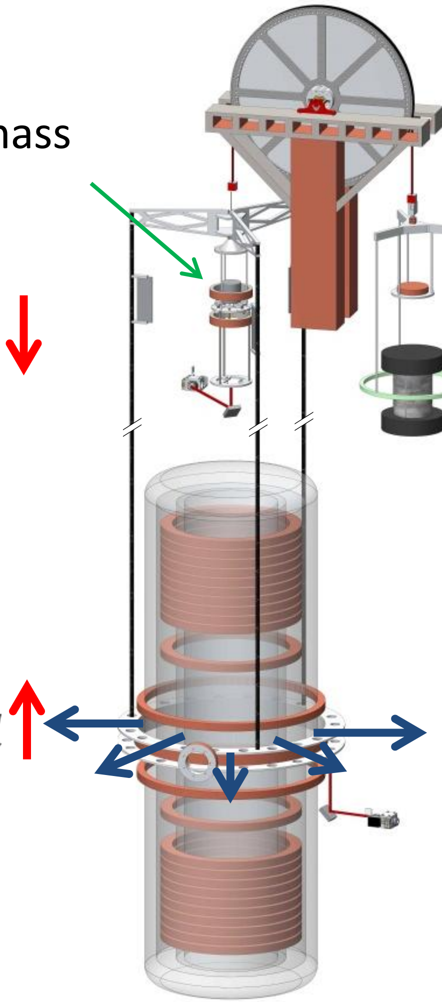
Principle of the watt balance in one slide

Force mode



$$mg = I\,Bl \qquad V = v\,Bl$$

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$$mgv = VI$$

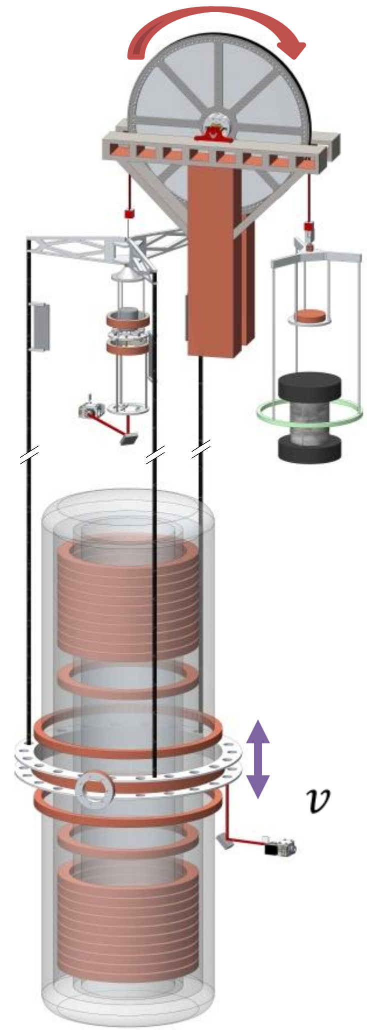
$$mgv = V_1 \frac{V_2}{R}$$

$$mgv = n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e} \frac{1}{r} \frac{e^2}{h}$$

$$mgv = \frac{n_1 n_2}{4r} f_1 f_2 h$$

$$h = \frac{4r}{n_1 n_2} \frac{mgv}{f_1 f_2}$$

Velocity mode



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The evolutions of NIST watt balances

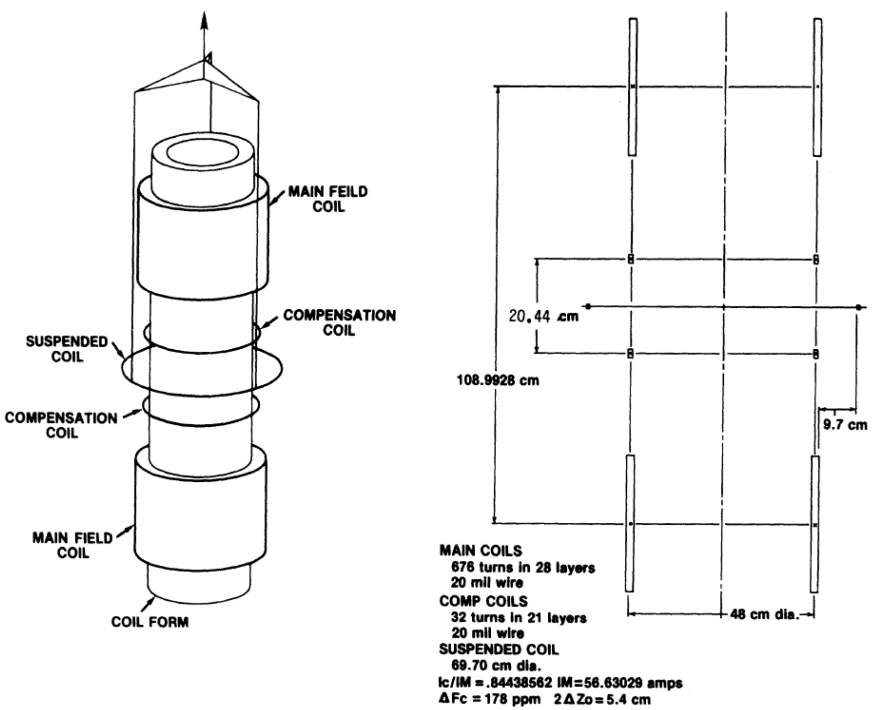
1980: about 4 years after Kibble's proposal.

234 IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. IM-29, NO. 4, DECEMBER 1980

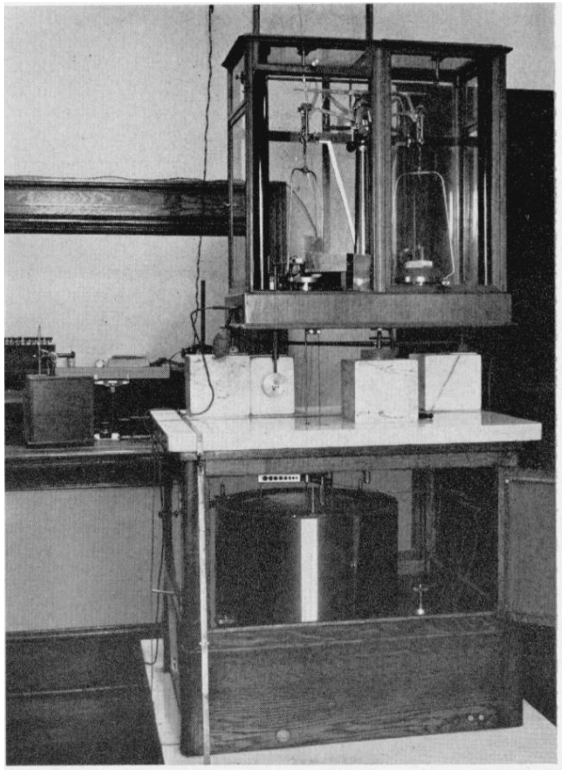
The Realization of the Ampere at NBS

PAUL T. OLSEN, MEMBER, IEEE, MARVIN E. CAGE, WILLIAM D. PHILLIPS, AND EDWIN R. WILLIAMS

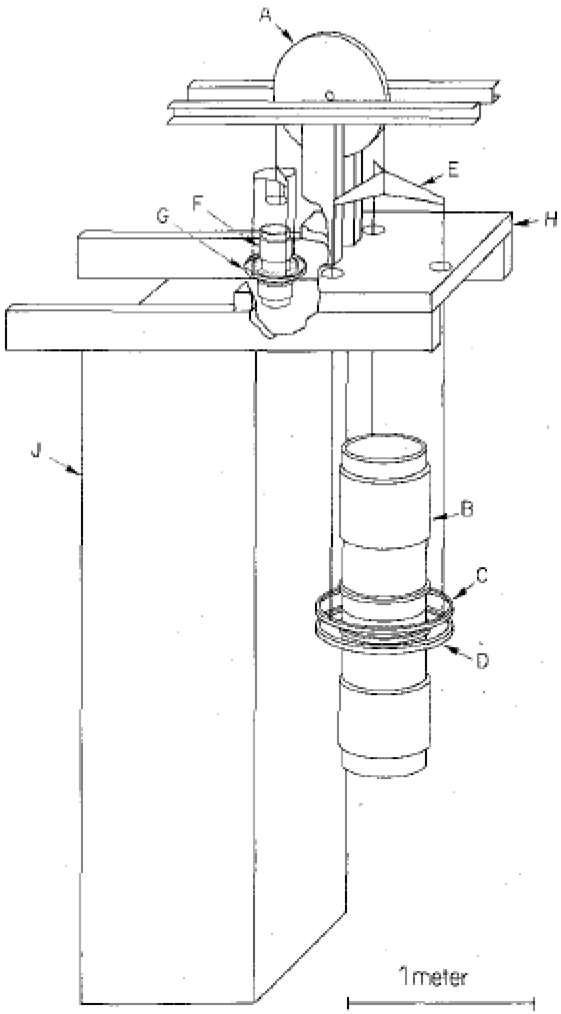
(a)



(b)

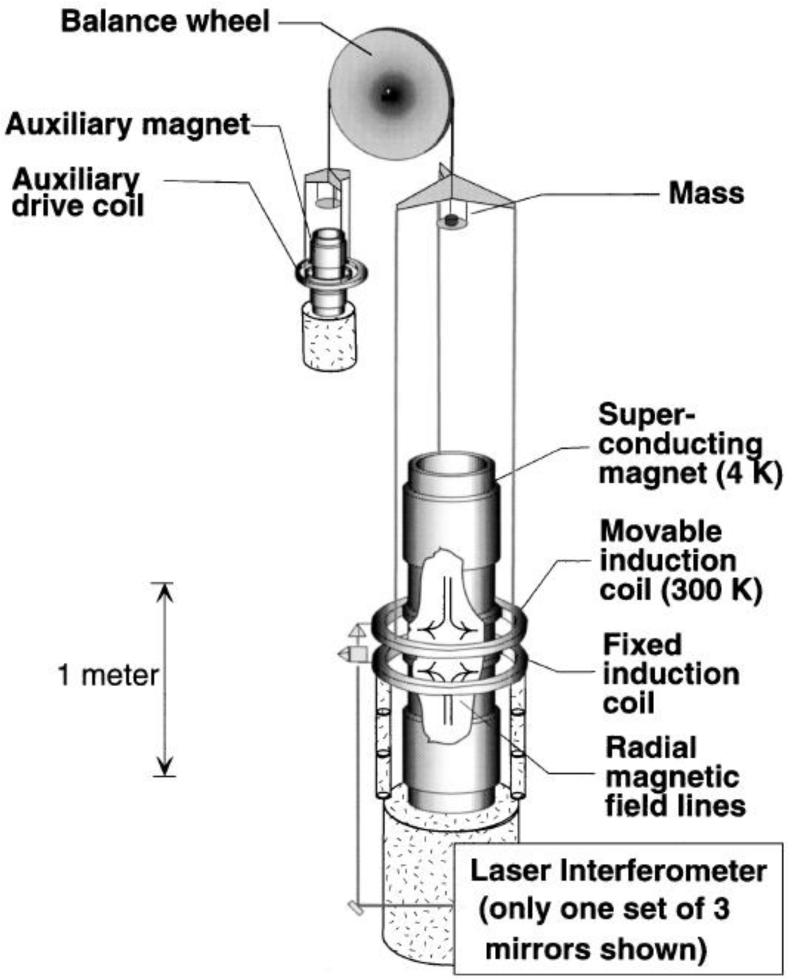


NIST-1



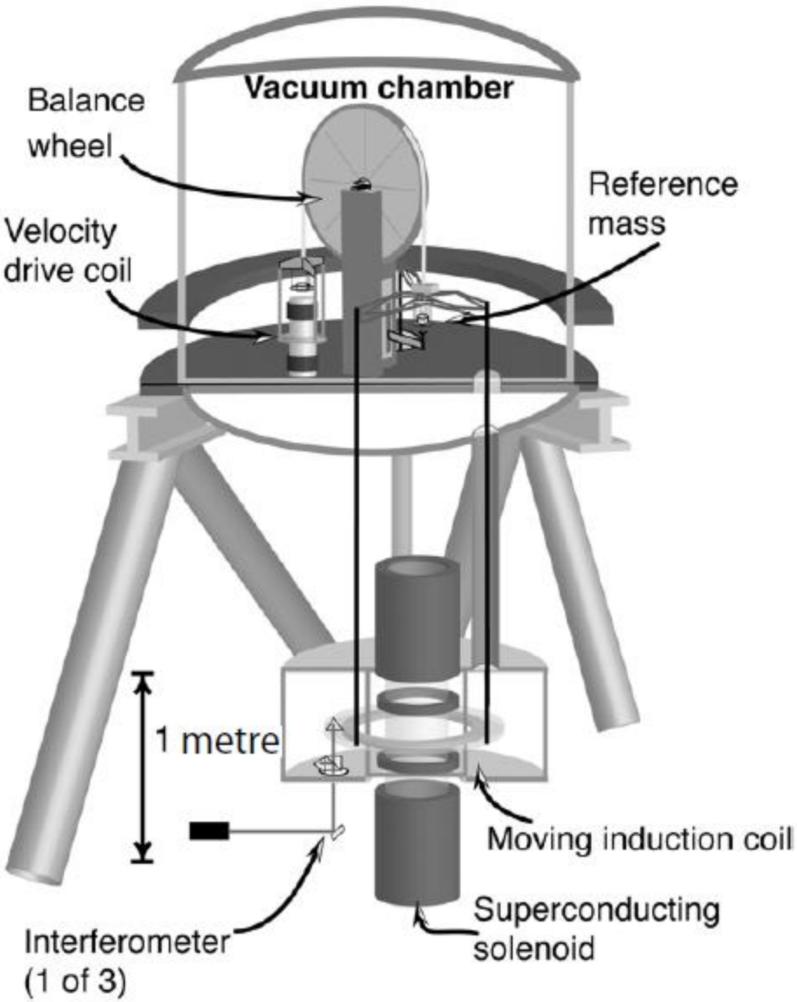
- Result published in 1989
- Rel. uncertainty: 1.3×10^{-6}
- Measurement in air.
- Conventional electromagnet
- 10.5 g gold mass.
- Bl = 21

NIST-2



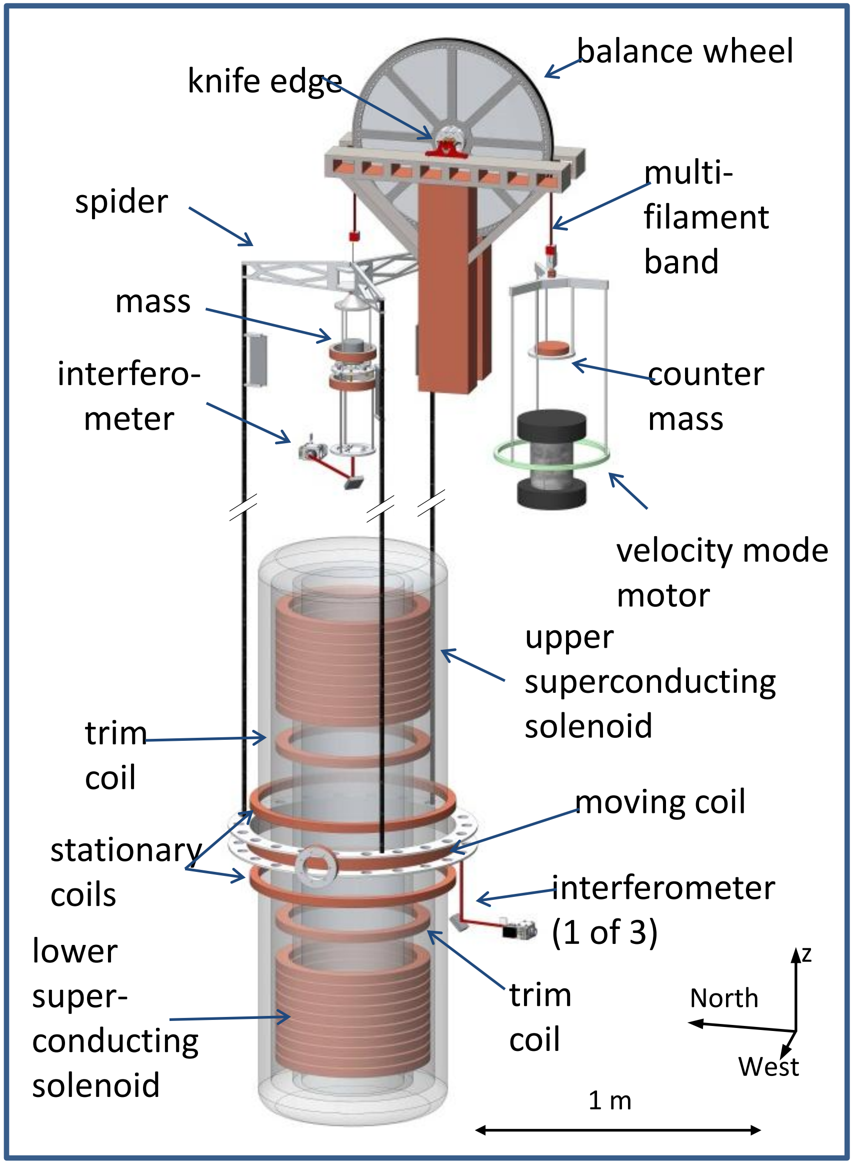
- Result published in 1998
- Rel. uncertainty: 8.7×10^{-8}
- Measurement in air.
- 1 kg gold mass
- Bl = 481
- Superconducting magnet system

NIST-3



- Used with K85 since 2003.
- Rel. uncertainty: 5.7×10^{-8}
- Measurement in vacuum.
- 1 kg PtIr mass (K85).
- in vacuum
- Bl = 481
- Superconducting magnet system

NIST-3 our workhorse for 15 years



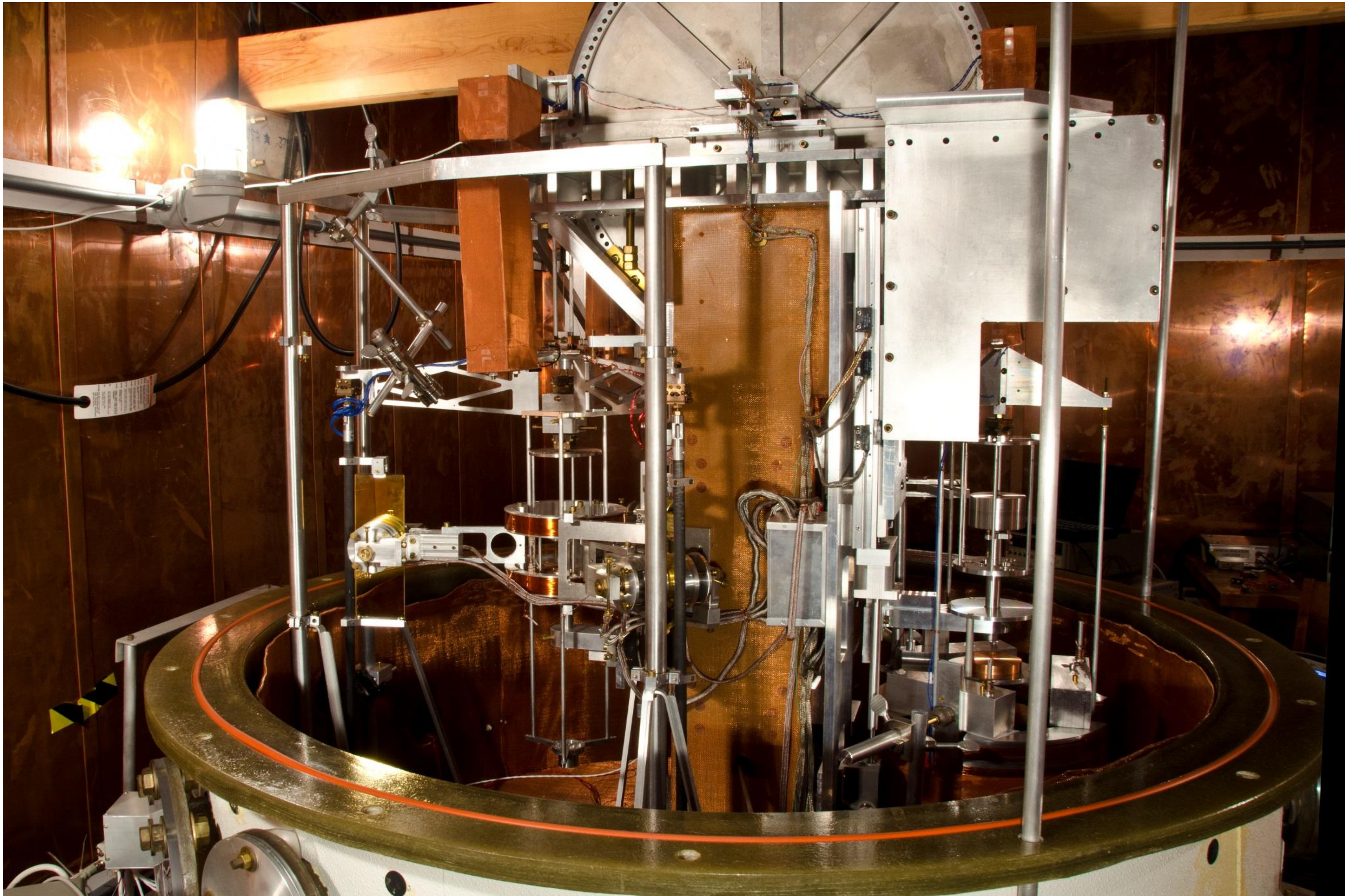
Distinctive feature:

Superconducting Magnet System

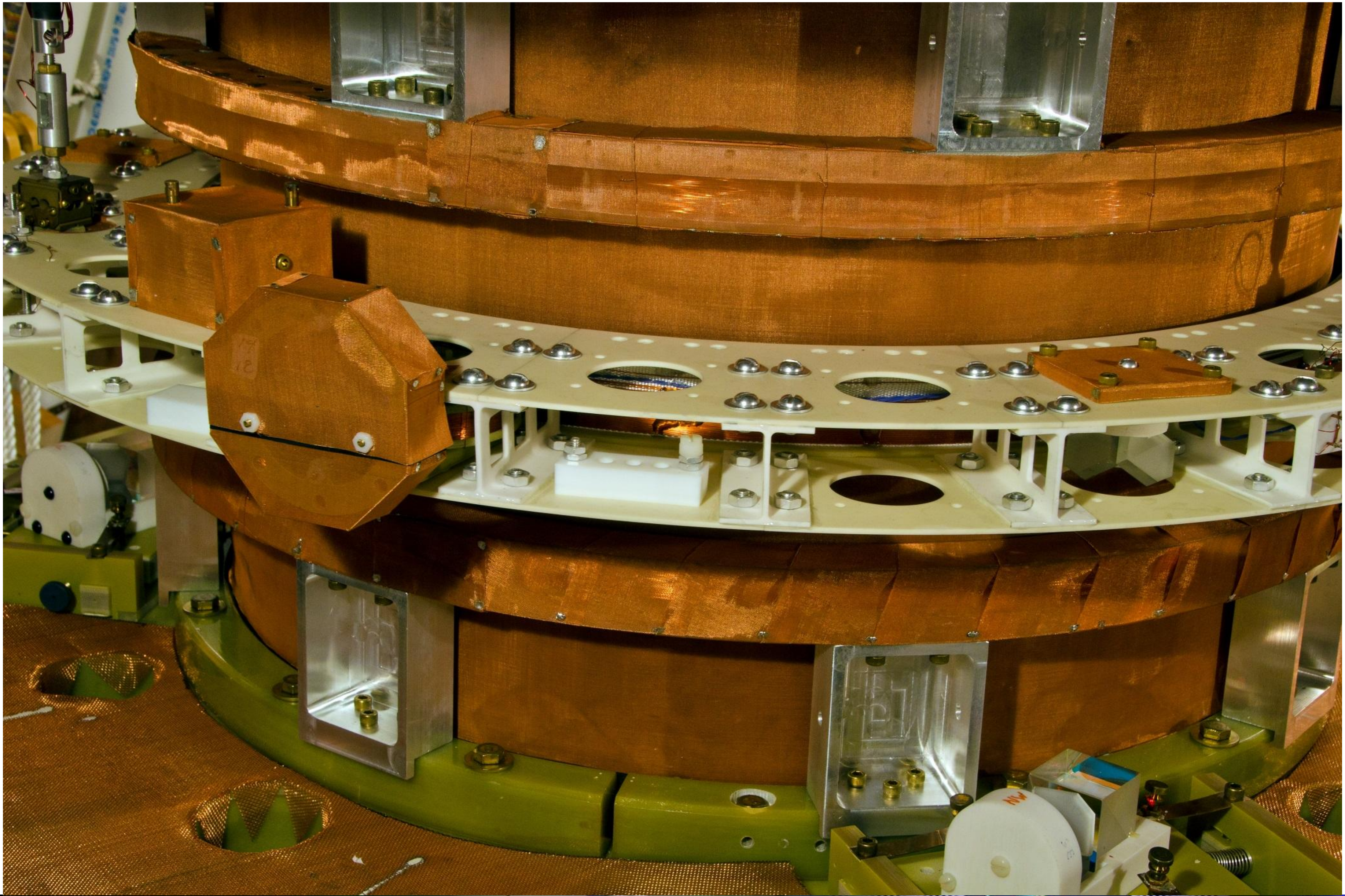
- Current is not persistent.
- Field is in principle calculable.
- $B(r) \propto 1/r$.
- Relative small field $B \approx 0.1$ T.
- Field can be changed.
- Iron free.
- Tall structure.
- Moving coil has large radius.
- Infinite gap.
- Easy access to moving coil.

$$h_{90} \equiv \frac{4}{K^2{}_{J-90} R_{K-90}} = 6.626\,068\,854\ldots \times 10^{-34}\ \mathrm{Js}$$

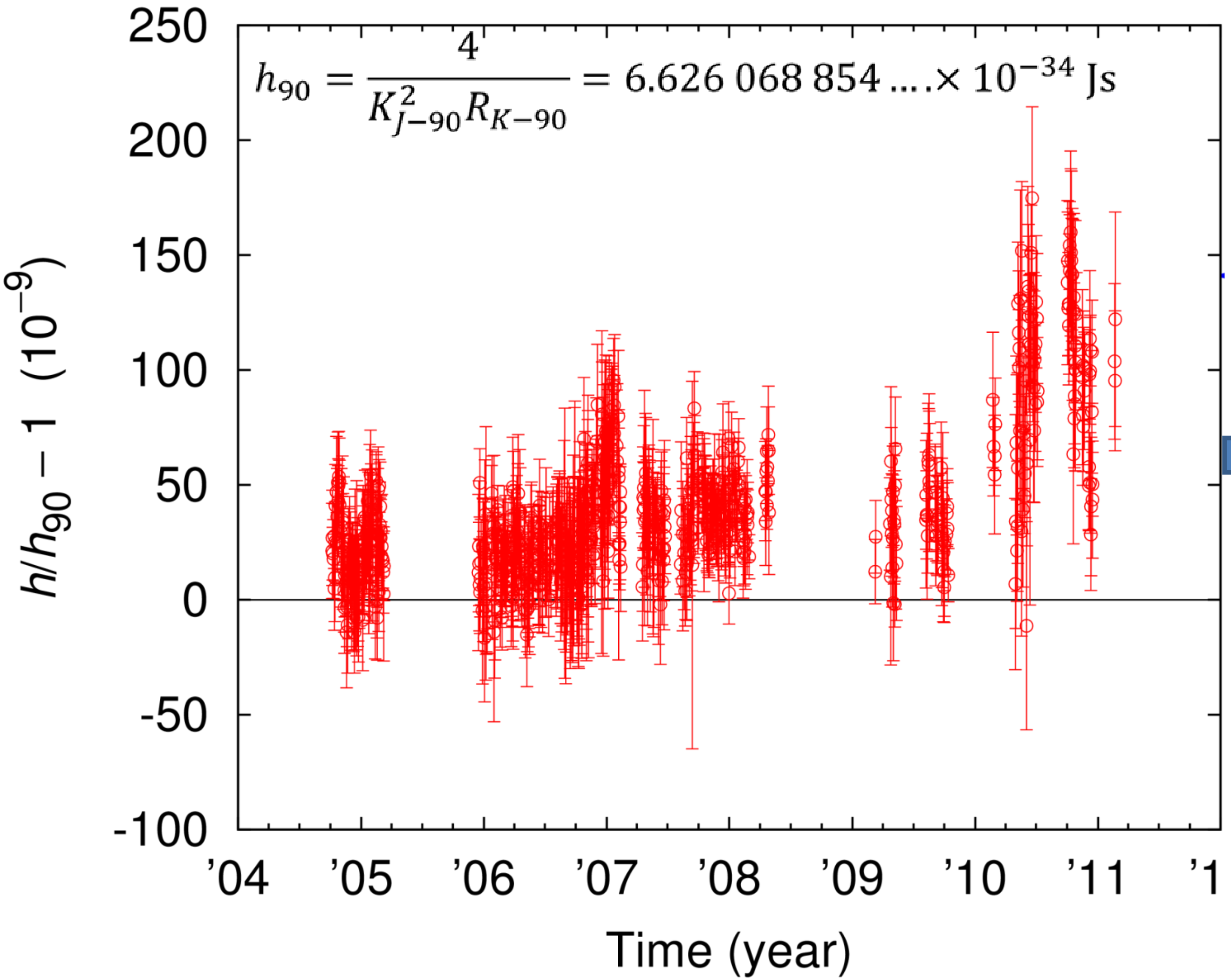
Upper part



Moving coil



Data up to Oct. 2011



2012/2013 measurement campaign

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Measurement plan 2012-2013

01Oct 2011

new team starts working on NIST-3

Solenoid cooled down

Alignment

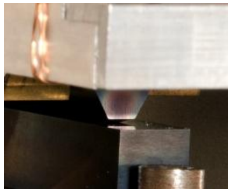
Assessment
Planning
Order of hardware

first quarter of data
uncertainties ≈100 x10^{-9}

Change of electrical grounding
New PJVS

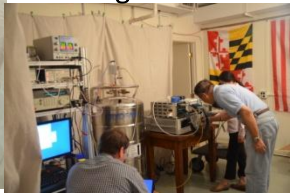
New
- current source
- vacuum pumps
- knife edge

Upgrades to
- Interferometers



Comparison of absolute gravimeter

Comparison of JJ Voltage Std.



Data analysis, systematic tests

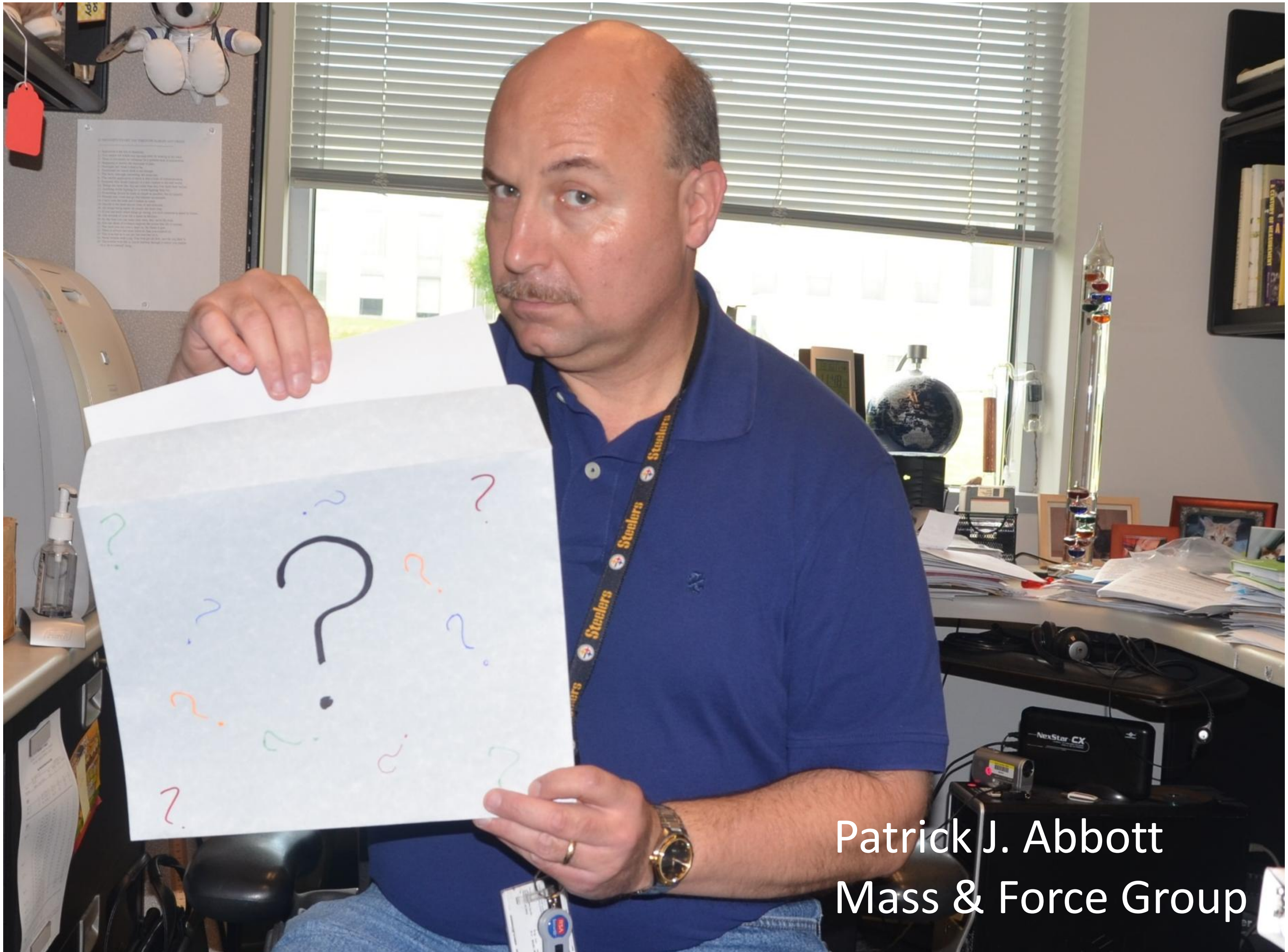
01Oct 2013

Goal: An independent data point with NIST-3
Independent measurement & uncertainty analysis

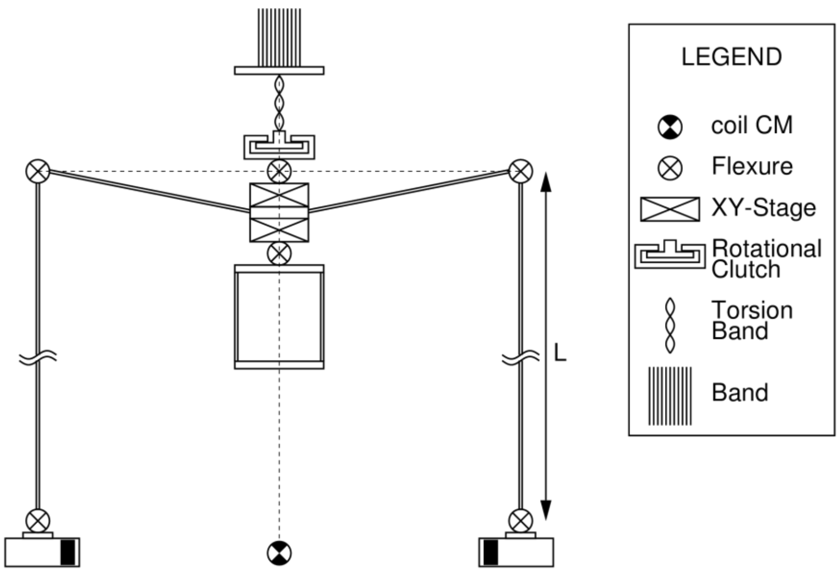
Improvements for this campaign

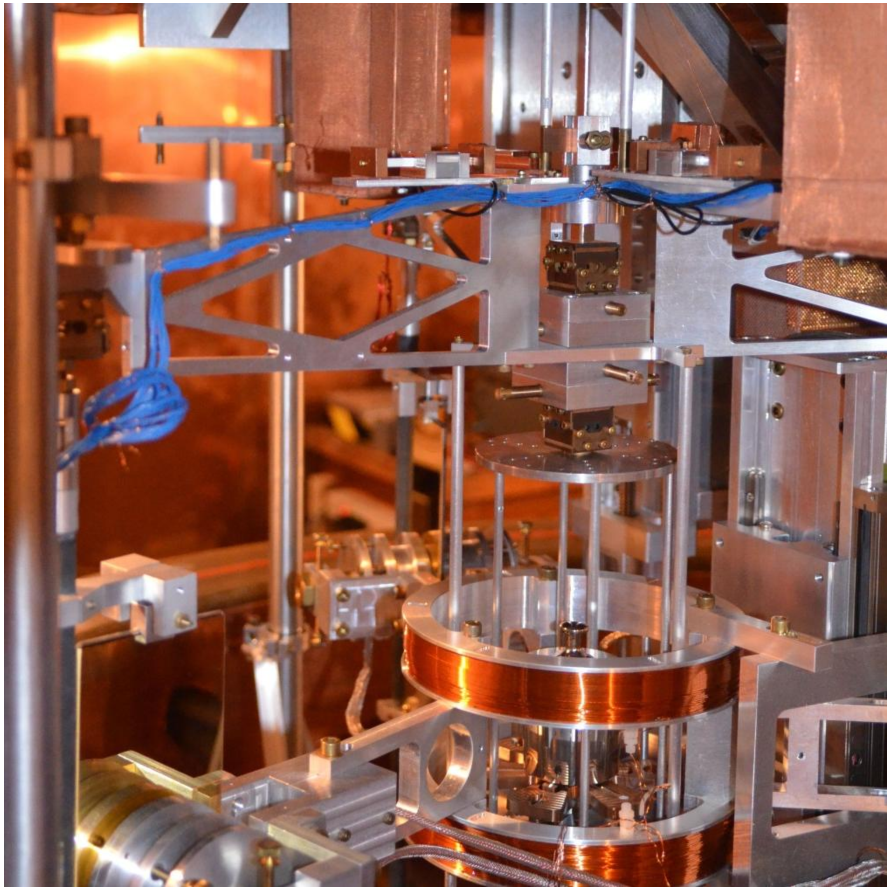
• Electrical:	Improved filters, grounding, guarding, power level.
• Environmental:	Better temperature stabilization.
• Mechanical:	New knife edge.
• Procedural:	Improved hysteresis erasing procedure.
• SW-control:	More channels logged.
• Electronics:	New low-noise current source.
• References:	New, calibrated laser. New bias electronics for Josephson Voltage standard. Josephson system was calibrated against US Volt. New determination of g. PtIr mass has been calibrated @ BIPM.
• Data analysis:	Second, largely independent analysis package.

Blind Measurement



Mass side stirrup





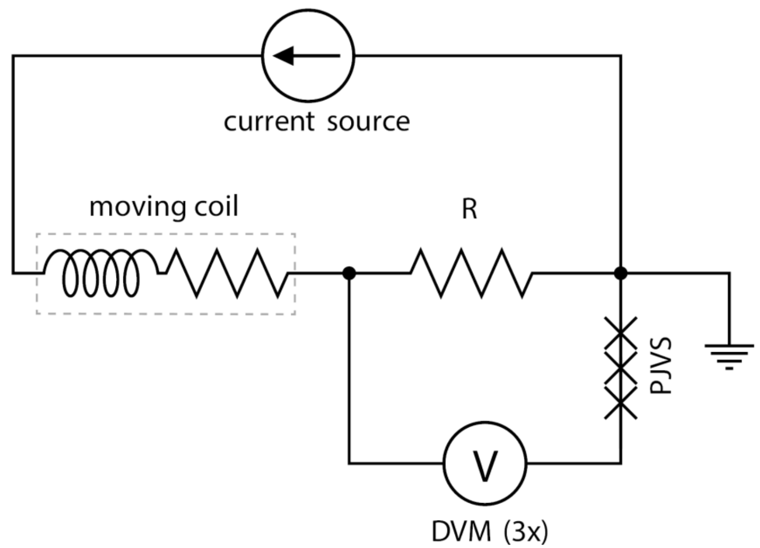
L=4.18 m,
m=25 kg

Wobble frequency:	0.537 Hz
Pendulum frequency:	0.241 Hz
Bounce frequency:	16 Hz
Sensitivity to torques:	2×10^{-5} Nm
Sensitivity to horiz. forces:	6×10^{-5} N

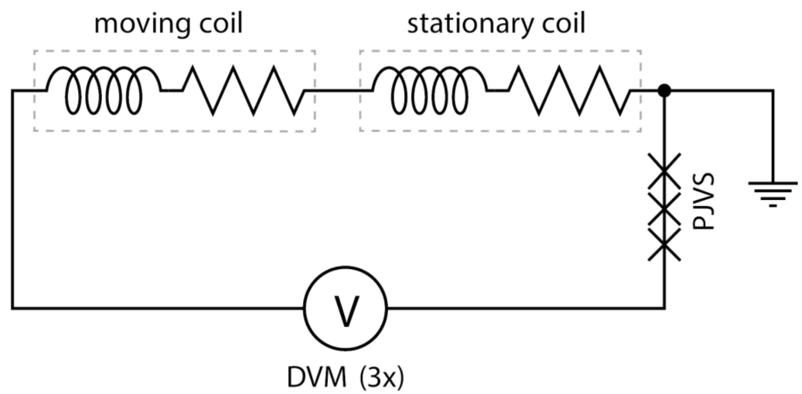
$$P_{\mathrm{mech}} = F_z v_z + F_x v_x + F_y v_y + N_x \omega_x + N_y \omega_y + N_z \omega_z$$

Electrical circuit

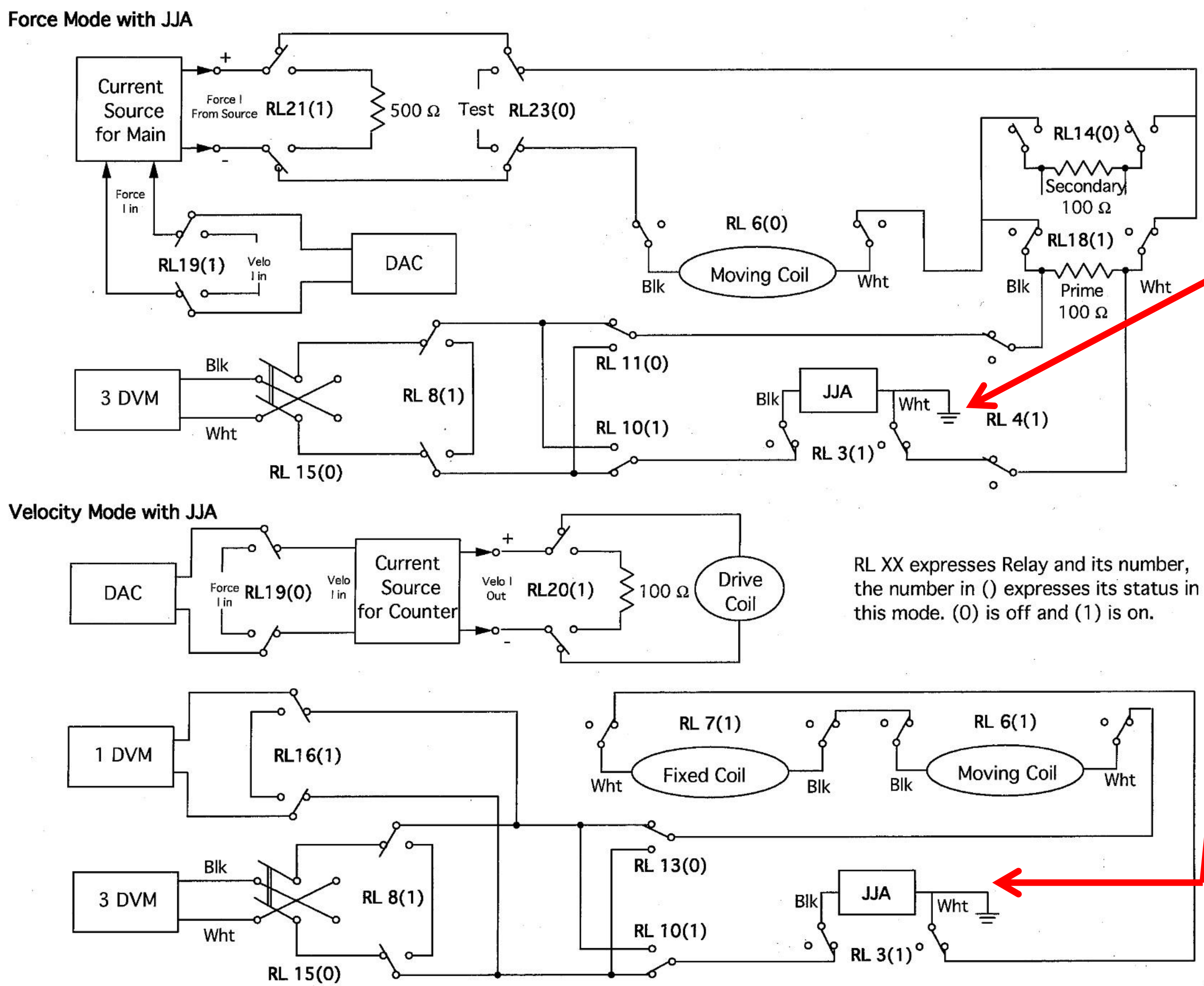
Force mode



Velocity mode



Switchbox



Measurements with and without GND were taken.

Concerns:

- Leakage
- Time dependent Leakage

Smallest measured leakage resistance to GND:
(76 ± 10) GΩ
⇒ 1.3 ppb rel. uncert.

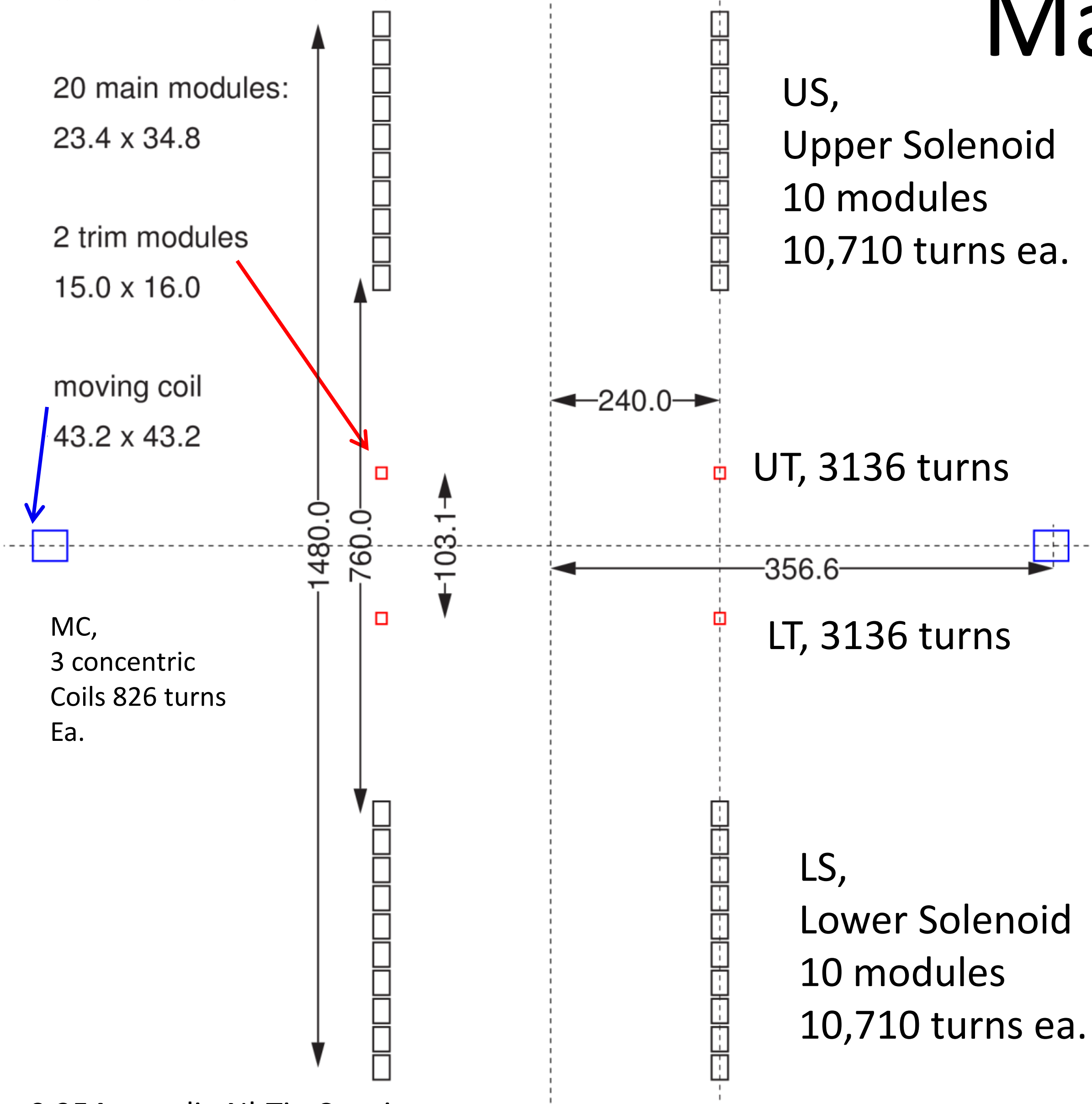
Magnetsystem

all dimensions mm dR x dH

20 main modules:
23.4 x 34.8

2 trim modules
15.0 x 16.0

moving coil
43.2 x 43.2



MC,
3 concentric
Coils 826 turns
Ea.

US,
Upper Solenoid
10 modules
10,710 turns ea.

UT, 3136 turns

LT, 3136 turns

LS,
Lower Solenoid
10 modules
10,710 turns ea.

Currents:

1. **Main 5 A (mostly)**
   US: cw
   UT: cw
   LT: ccw
   LS: ccw
2. **Skew 12.6 mA**
   US: cw
3. **Trim 59.2 mA**
   UT: ccw
   LT :ccw

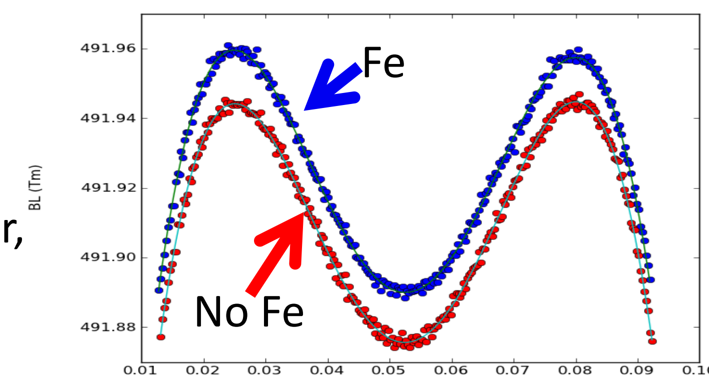
Force between US and LS:
@5A: 4821 N
@2A: 771 N

0.254 mm dia NbTi –Cu wire
On G10 bobbins, ~320 km

Concerns regarding the magnet system

- Surface currents due to Meissner Effect
  - BL during force mode is different due to persistent surface currents.
- Transient effects
  - Current ramp in moving coil changes super current.
- Transformer effect
  - AC in moving coil induces AC in super conductor. AC-AC coupling has net DC force.
- Iron
  - Nearby ferromagnetic material changes BL during force mode.

Iron cylinder,
24.3 kg



No change
in *h* observed!

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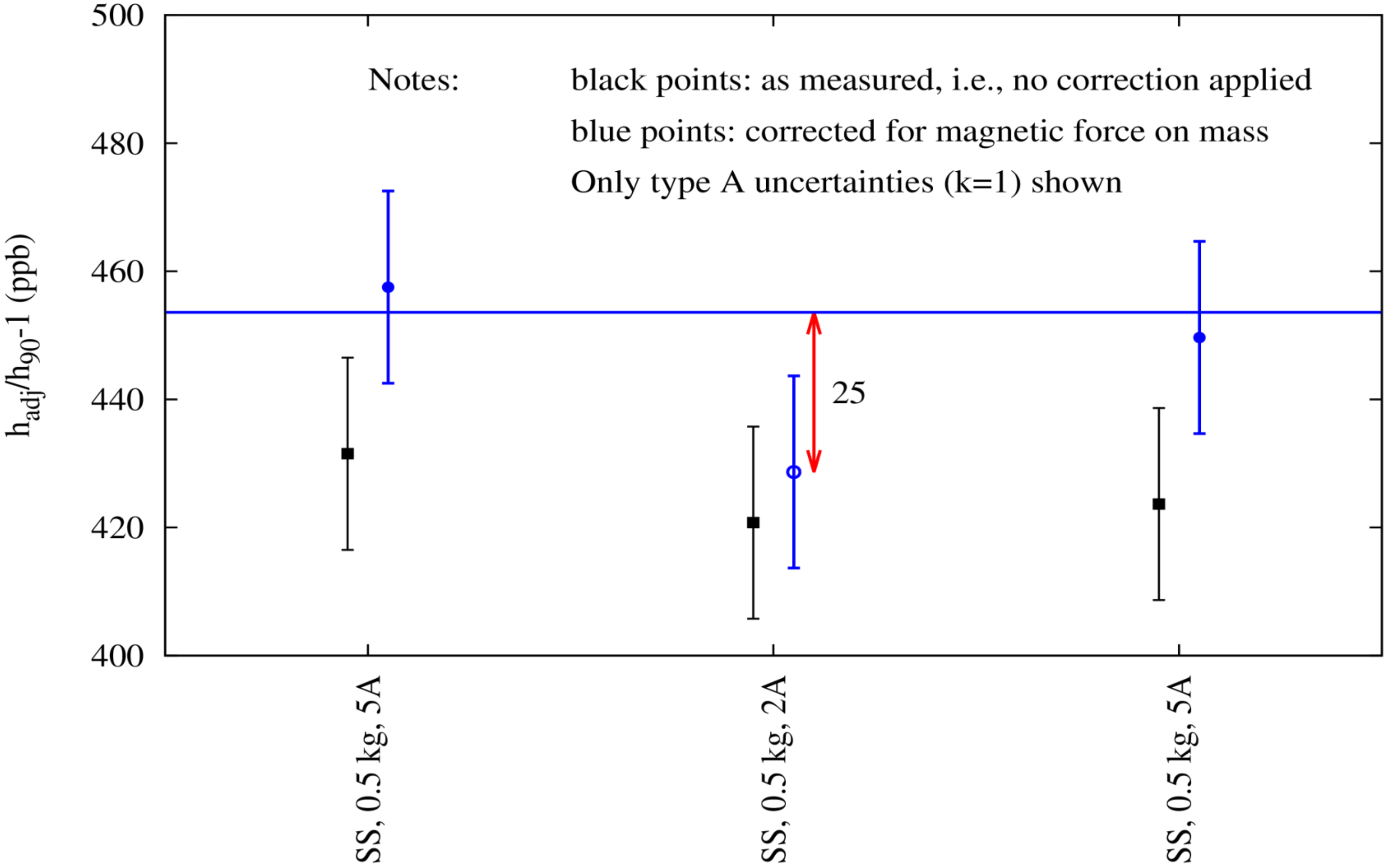
No big change between I_{SC}= 5 A and I_{SC}= 2 A observed.



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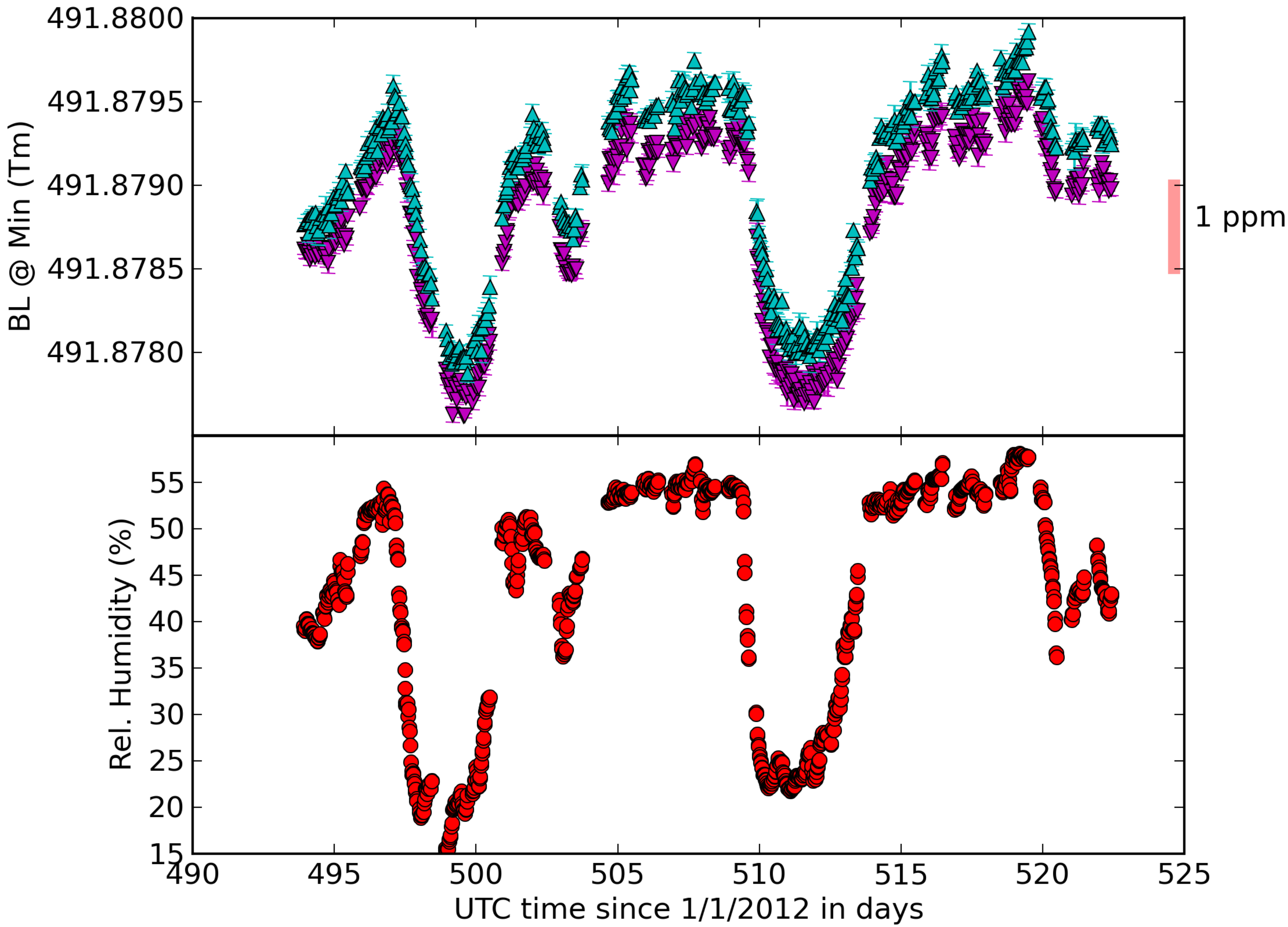
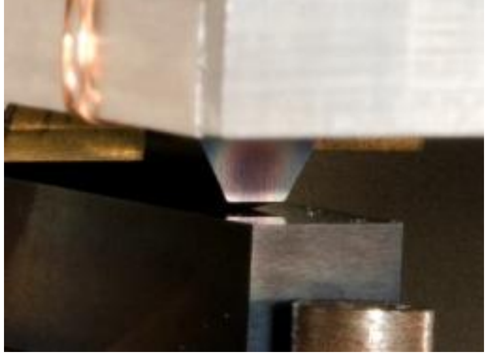
Stability of the magnetic field

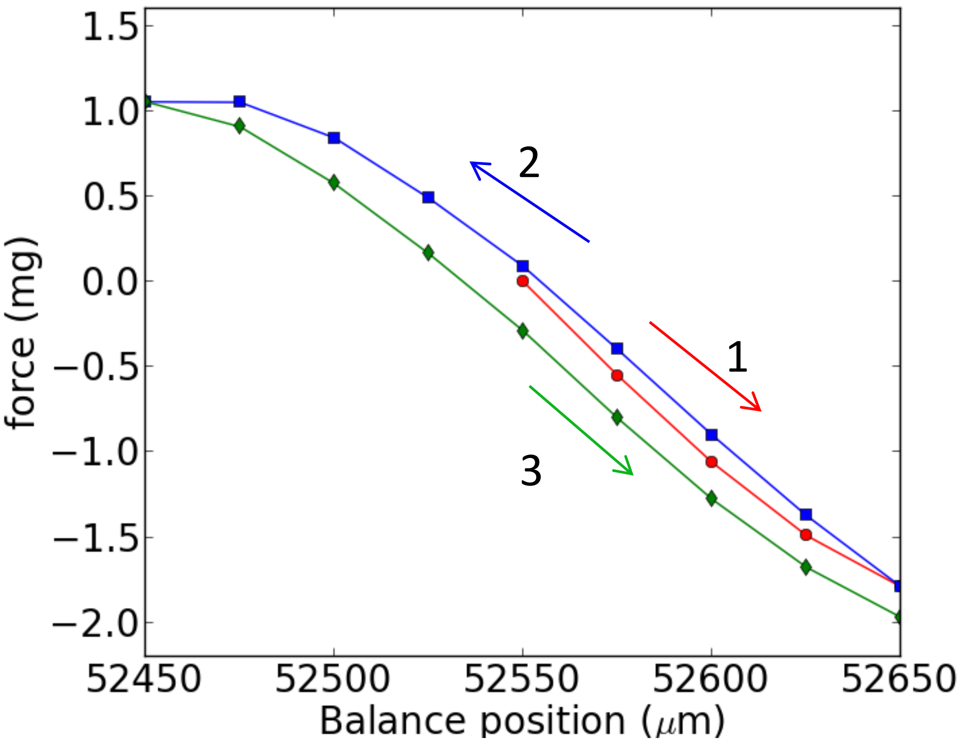


Physi

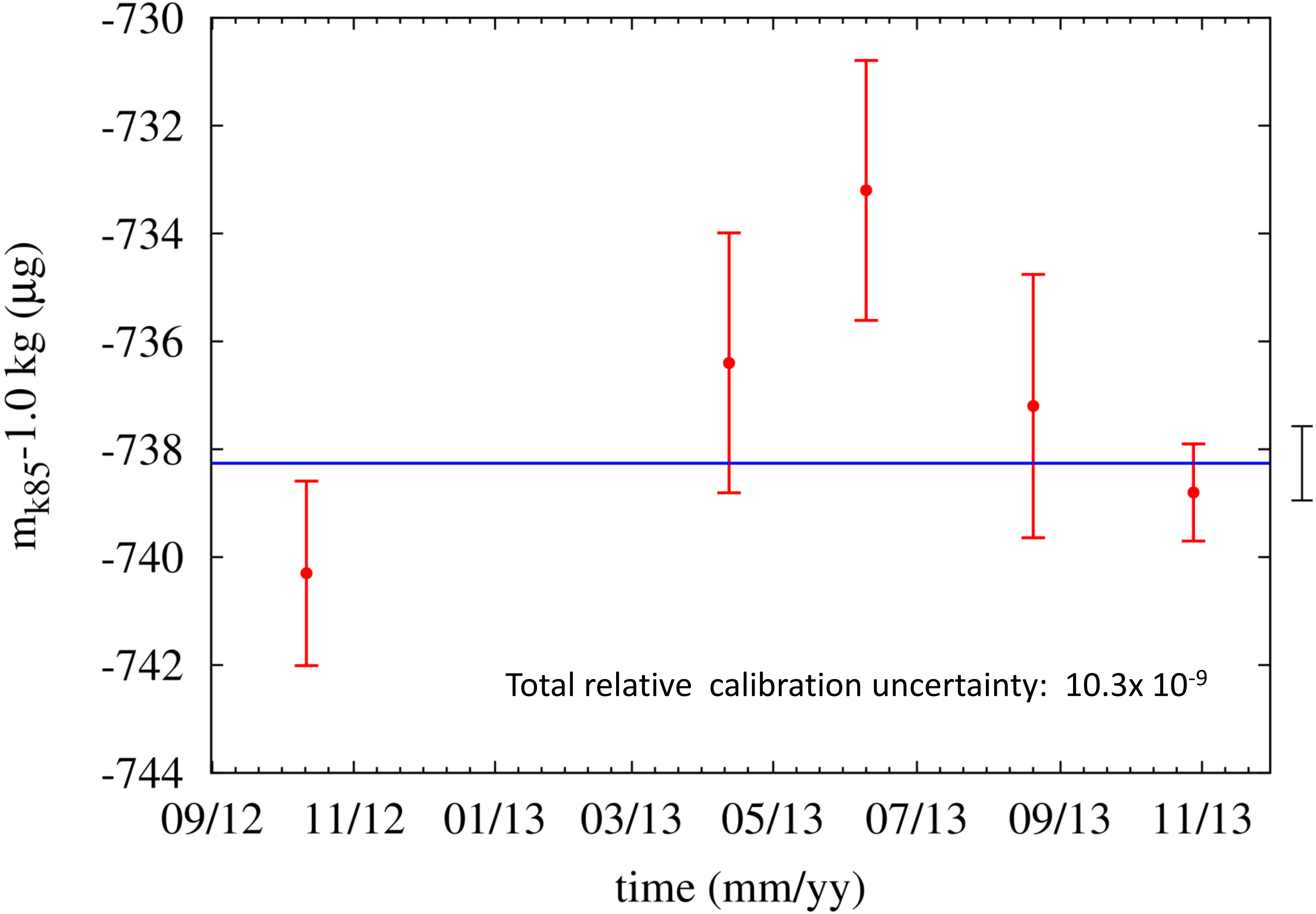


Knife edge

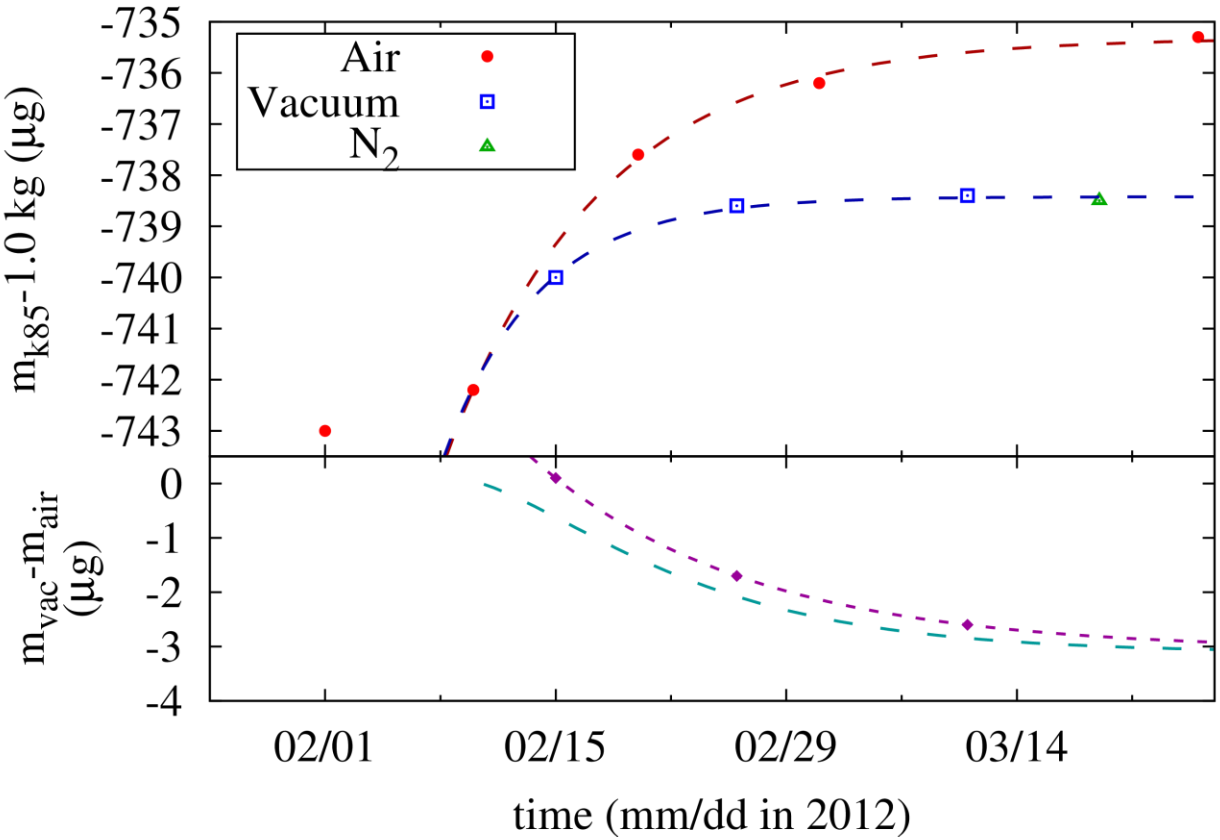
- Knife edge and flat are made from WC.
- It is coated with diamond like carbon.
- WC is magnetic.
- Knife edge was changed on 06/25/2012.
- Old knife edge was in use from 2010 to 2012.



Calibrations -- Mass



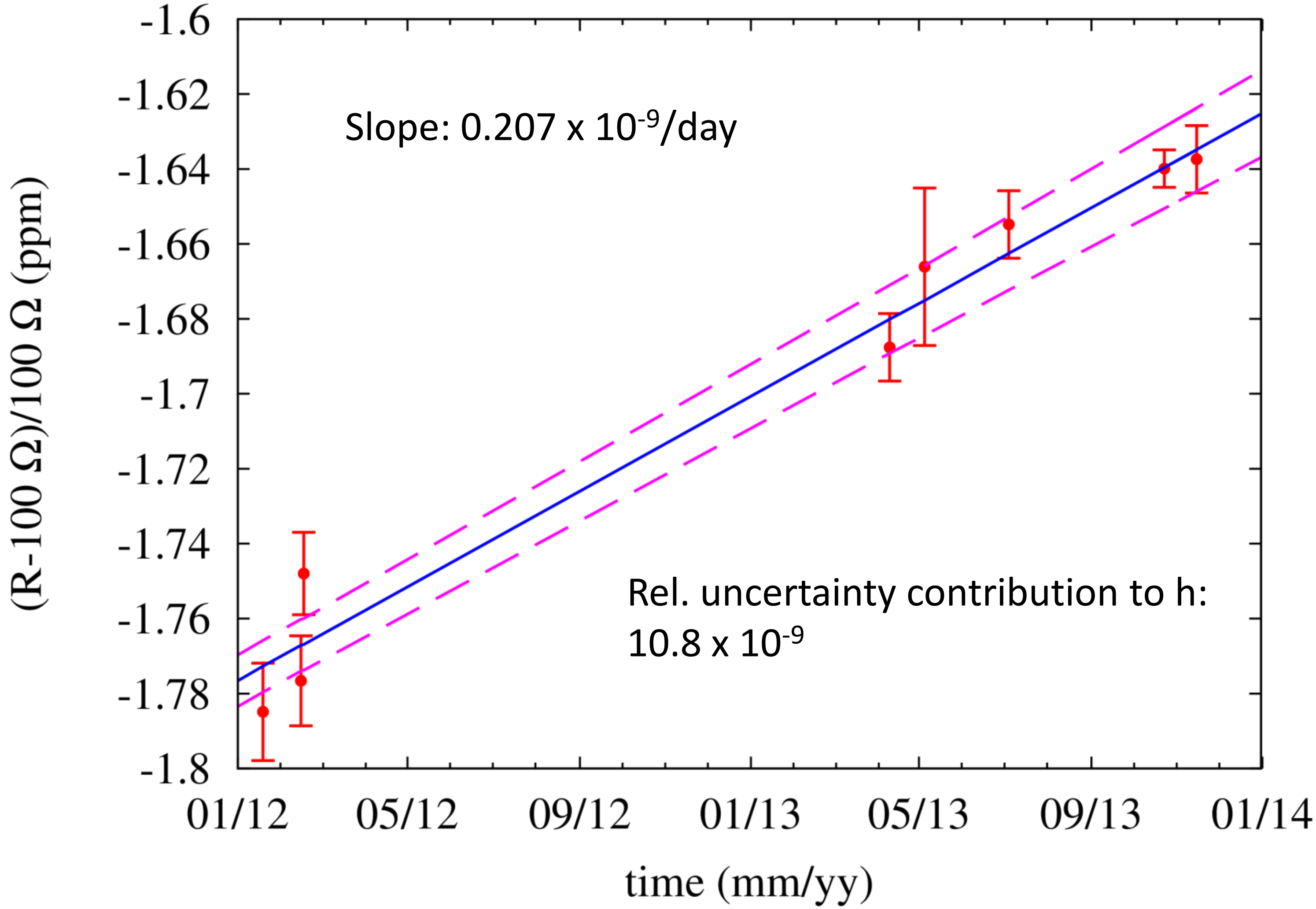
Mass - Sorption



Sorption effect:

3.11 µg ± 0.27 µg

Calibrations -- Resistance



Measurement procedure

- Servo moving coil to top, balance is controlled with counter mass motor

Repeat 9x

- Measure a velocity, coil sweeps from top down, takes about 40s
- Measure a velocity, coil sweeps from bottom up, takes about 40s

Repeat Nx (typical 11-13)

- Servo balance to middle, perform ZFLEX0 (+35 mm, -16 mm,..).
- Switch balance control to the moving coil. Move masses close
- Depending on how well the system is balanced the knife edge moves a little.
- Perform ZFLEX1 to erase the imprint of this motion on the knife edge
- Put Counter mass on, perform ZFLEX2 &3 takes about 5 min

Repeat 3x

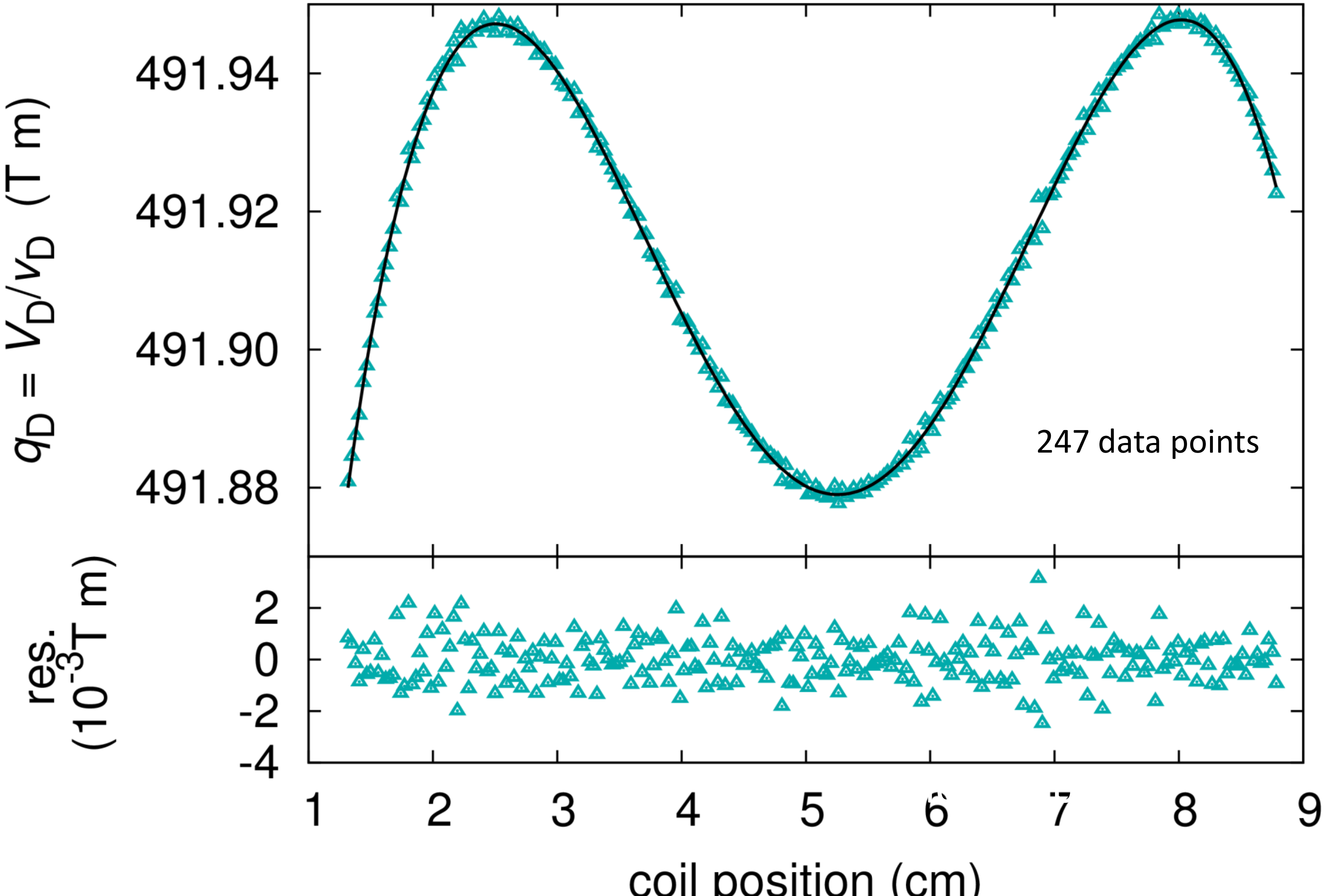
- Weighing takes about 100 s
- Put Main mass on, perform ZFLEX3 takes about 5 min
- Weighing takes about 100 s
- Take Main mass off, perform ZFLEX3 takes about 5 min
- Weighing takes about 100 s

- Servo balance to middle, remove masses, switch control to CM motor
- Servo balance to top, balanced is controlled with counter mass motor

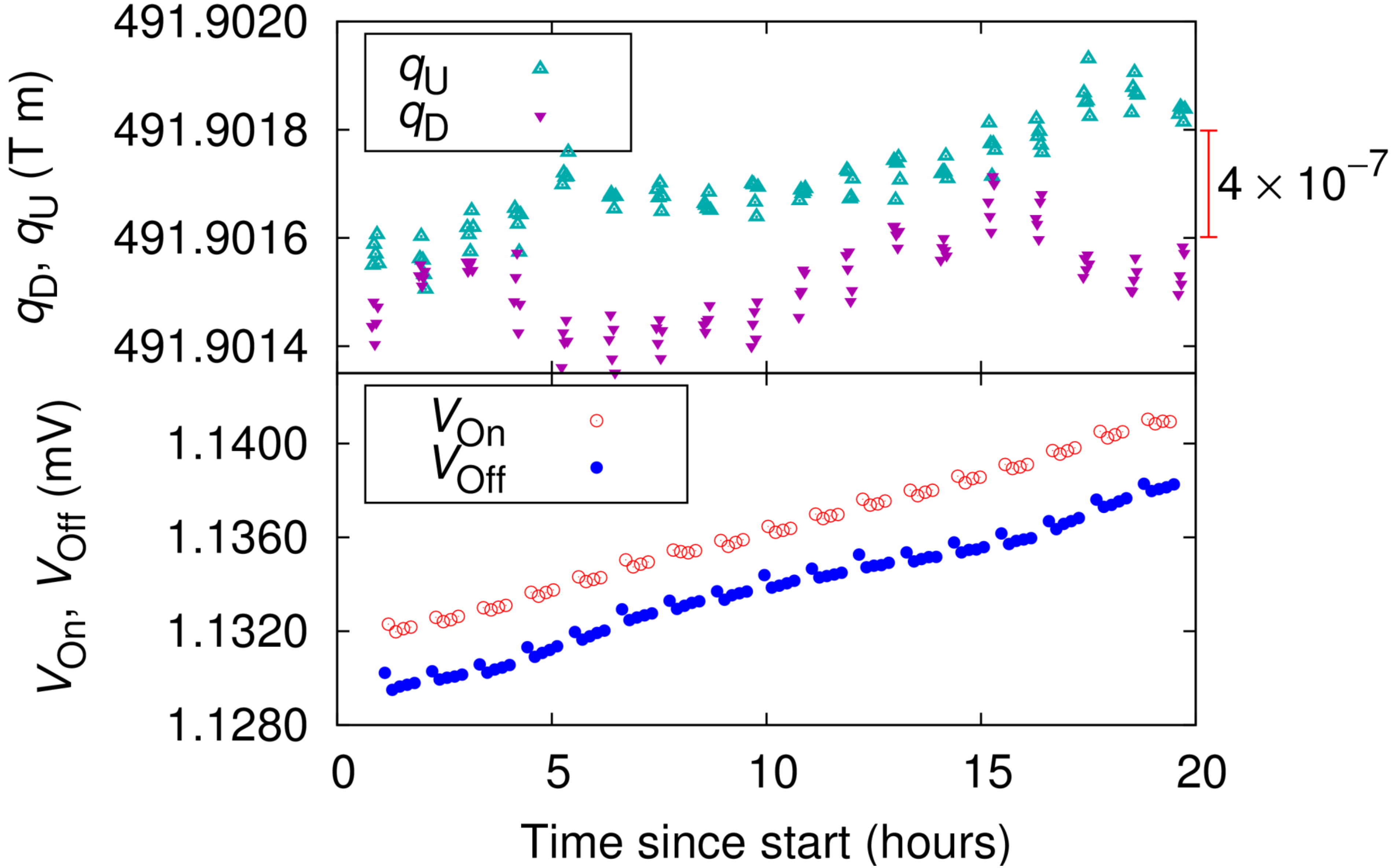
Repeat 9x

- Measure a velocity, coil sweeps from top down, takes about 40s
- Measure a velocity, coil sweeps from bottom up takes about 40s

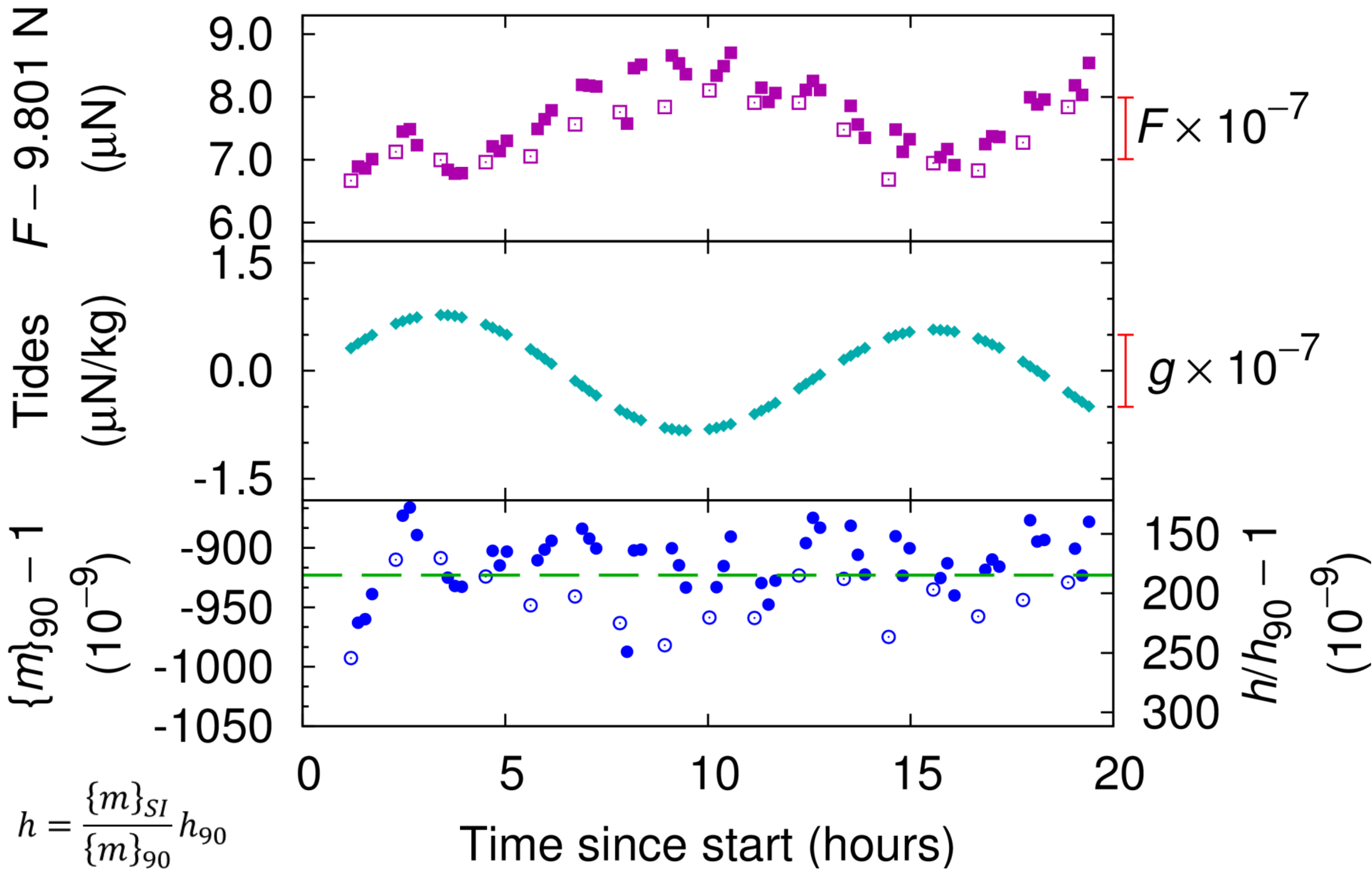
One velocity sweep



Typical data

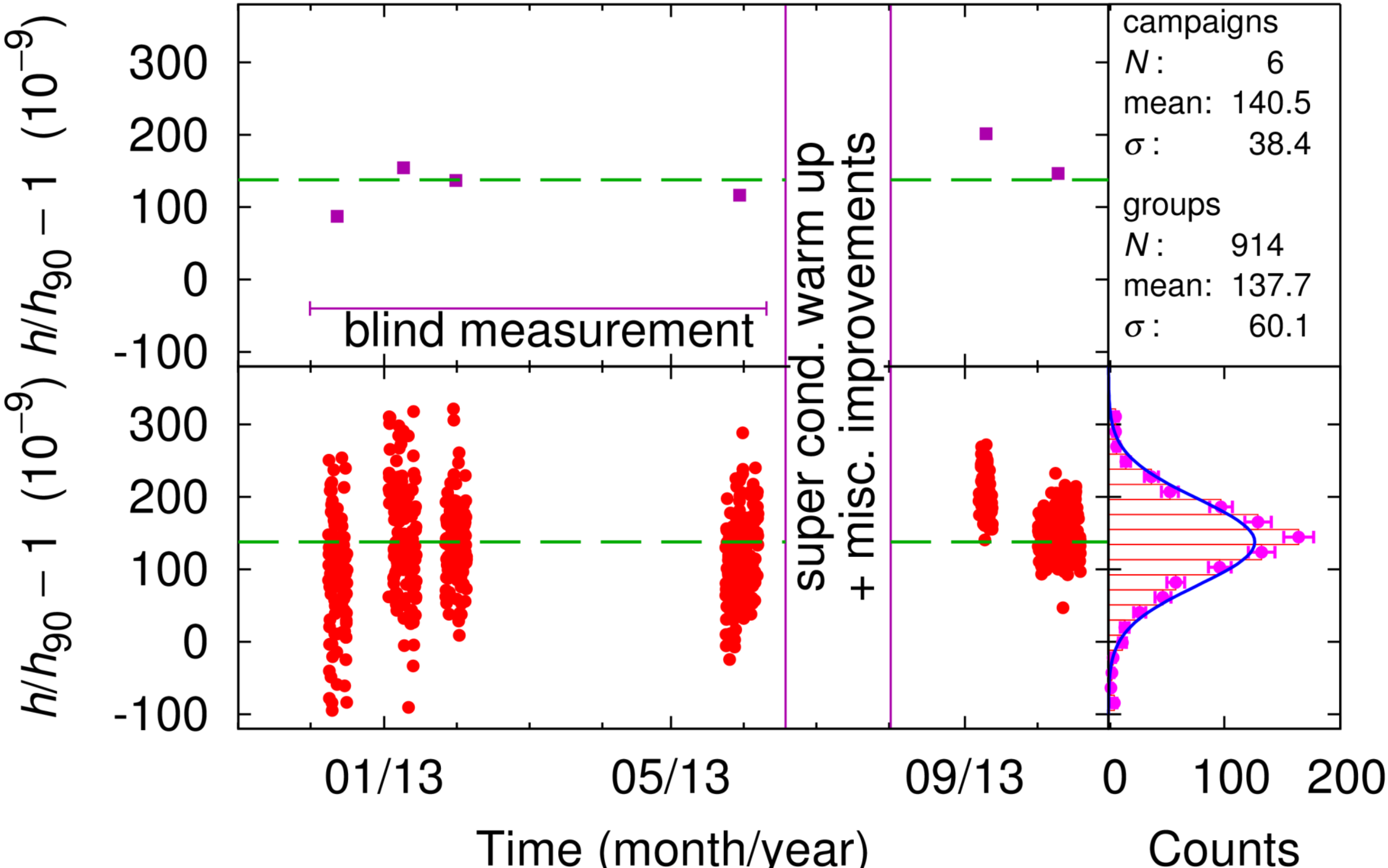


Typical data



$$h = \frac{\{m\}_{SI}}{\{m\}_{90}} h_{90}$$

Results


campaigns
N: 6
mean: 140.5
σ: 38.4
groups
N: 914
mean: 137.7
σ: 60.1
blind measurement
super cond. warm up
+ misc. improvements
h/h90 − 1 (10−9)
300
200
100
0
-100
01/13
05/13
09/13
0
100
200
Time (month/year)
Counts

Uncertainty budget and final result

Source	rel. std. uncertainty k=1 (10^{-9})
Balance mechanics	21.4
Alignment	20.0
Magnetic field	19.4
Electrical	16.1
Statistical	15.7
Velocity	10.6
Mass metrology	9.7
Local acceleration	7.1
Combined	44.7

$$h = 6.626\,069\,79(30) \times 10^{-34}\ \mathrm{Js}$$

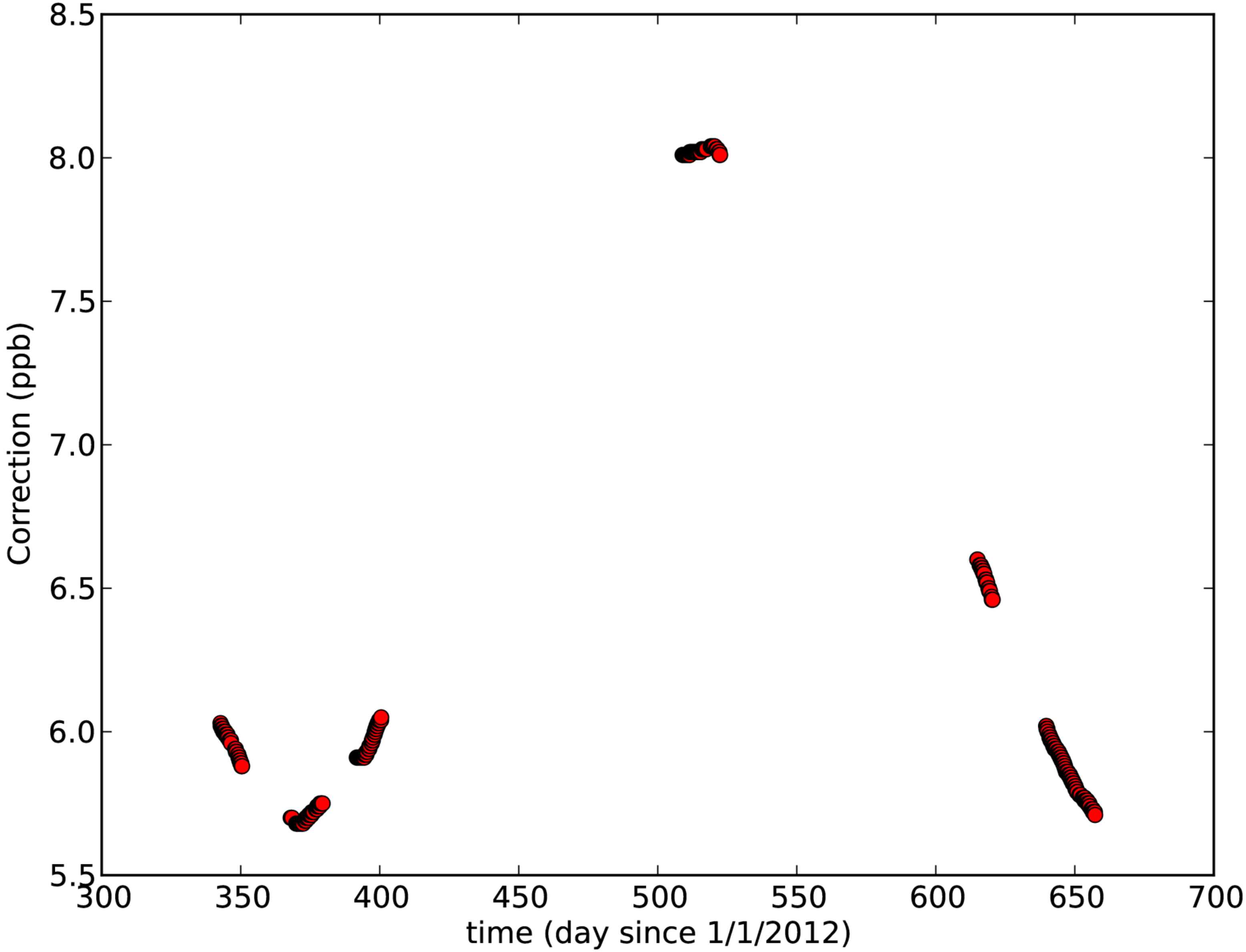
$$\frac{h}{h_{90}} - 1 = 141(45) \times 10^{-9}$$

$$P_{\mathrm{mech}} = F_z v_z + F_x v_x + F_y v_y + N_x \omega_x + N_y \omega_y + N_z \omega_z$$

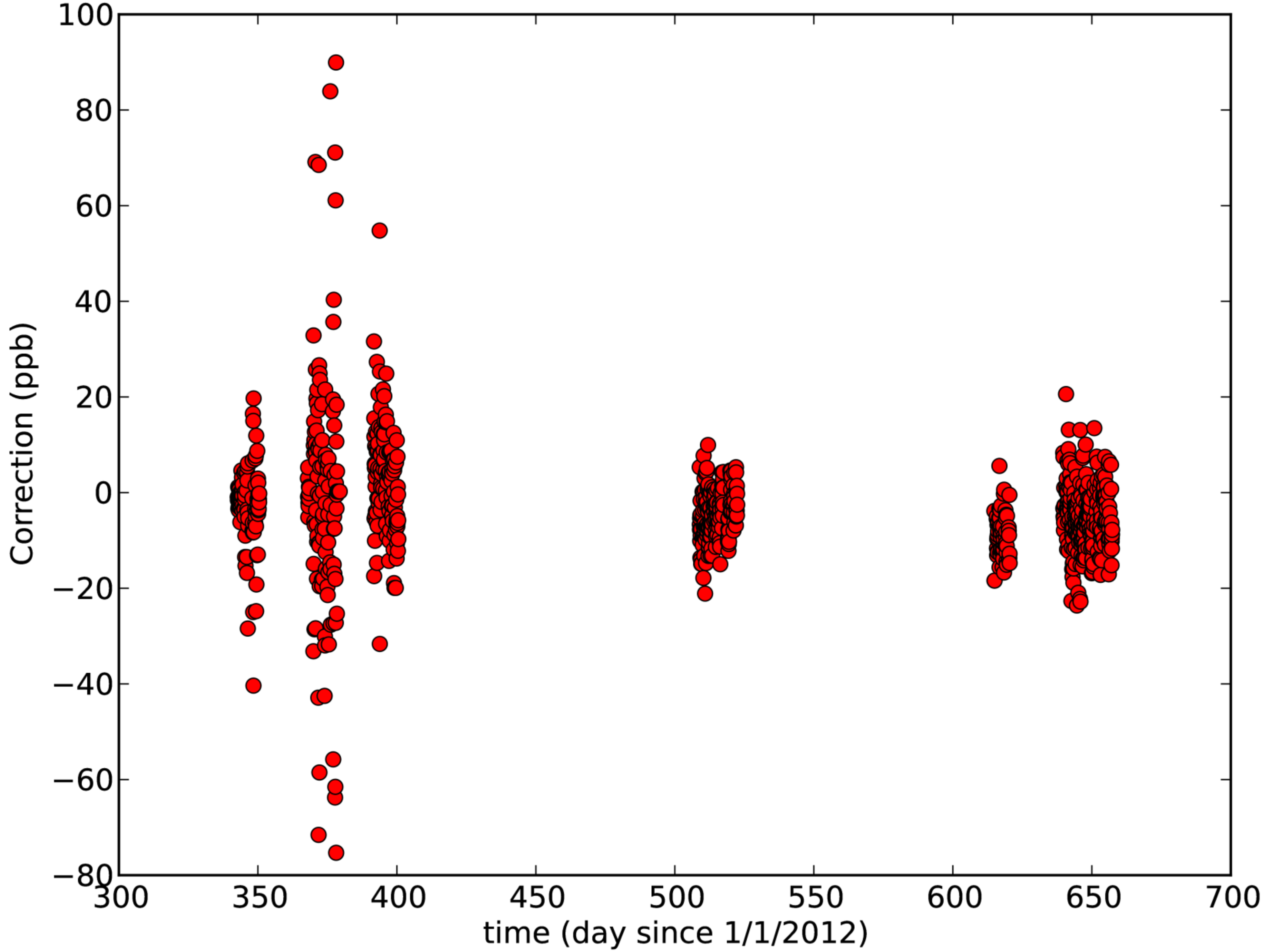
Corrections

Source	Fractional correction (10^{-9})
Polar motion on g	+6.4
Dynamic knife edge hysteresis	-6.3
Alignment	-3.3
Water desorption on mass	-3.1
Diffraction of interferometer beams	+2.8
Air pressure variations on g	-2.1
Verticality of the interferometer beams	2.1
Refractive index of residual air	-1.2
Tidal variation of g	-0.8
PJVS leakage	+0.4
Buoyancy on the mass by residual air	-0.2
Magnetic forces on K85	+0.1
DVM gain correction	0.0
Total	-5.3

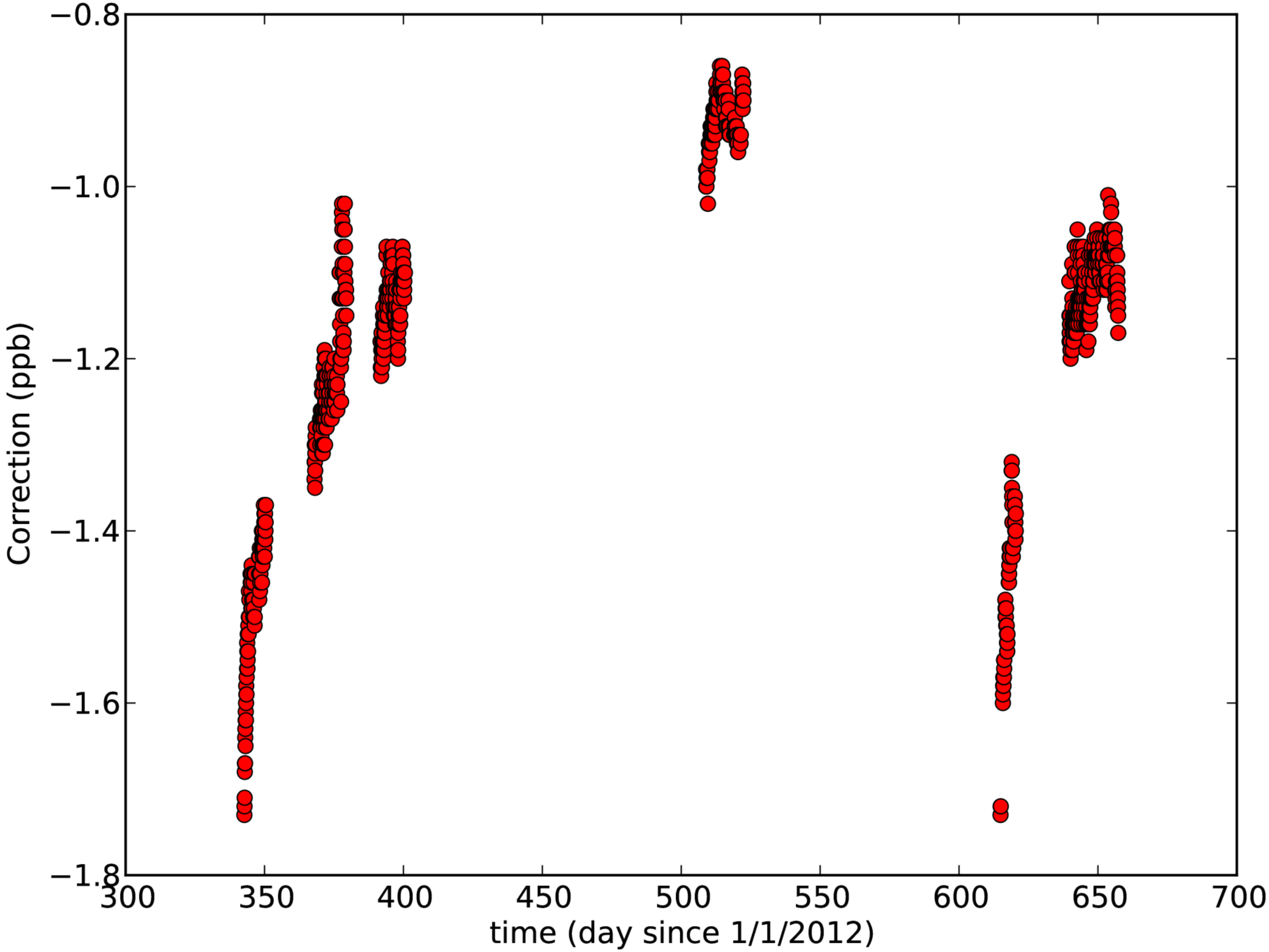
Polar motion correction



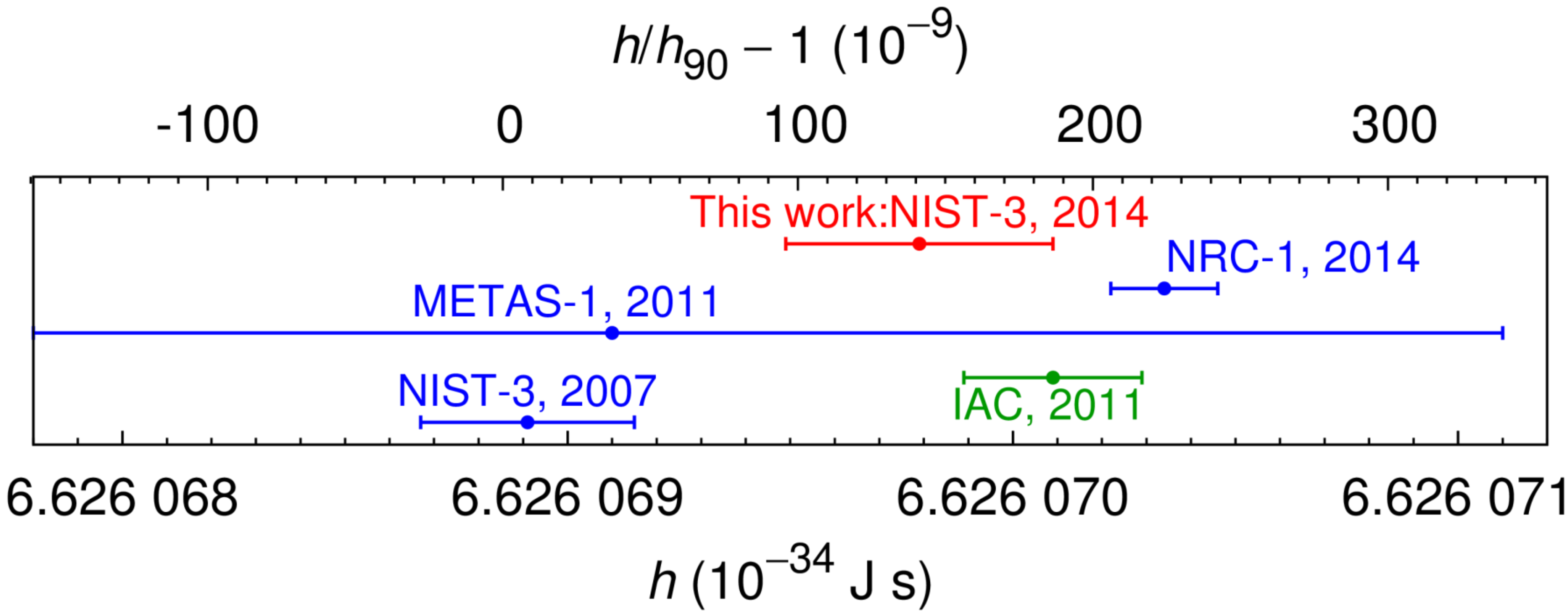
Correction due to alignment



Correction due to index of refraction



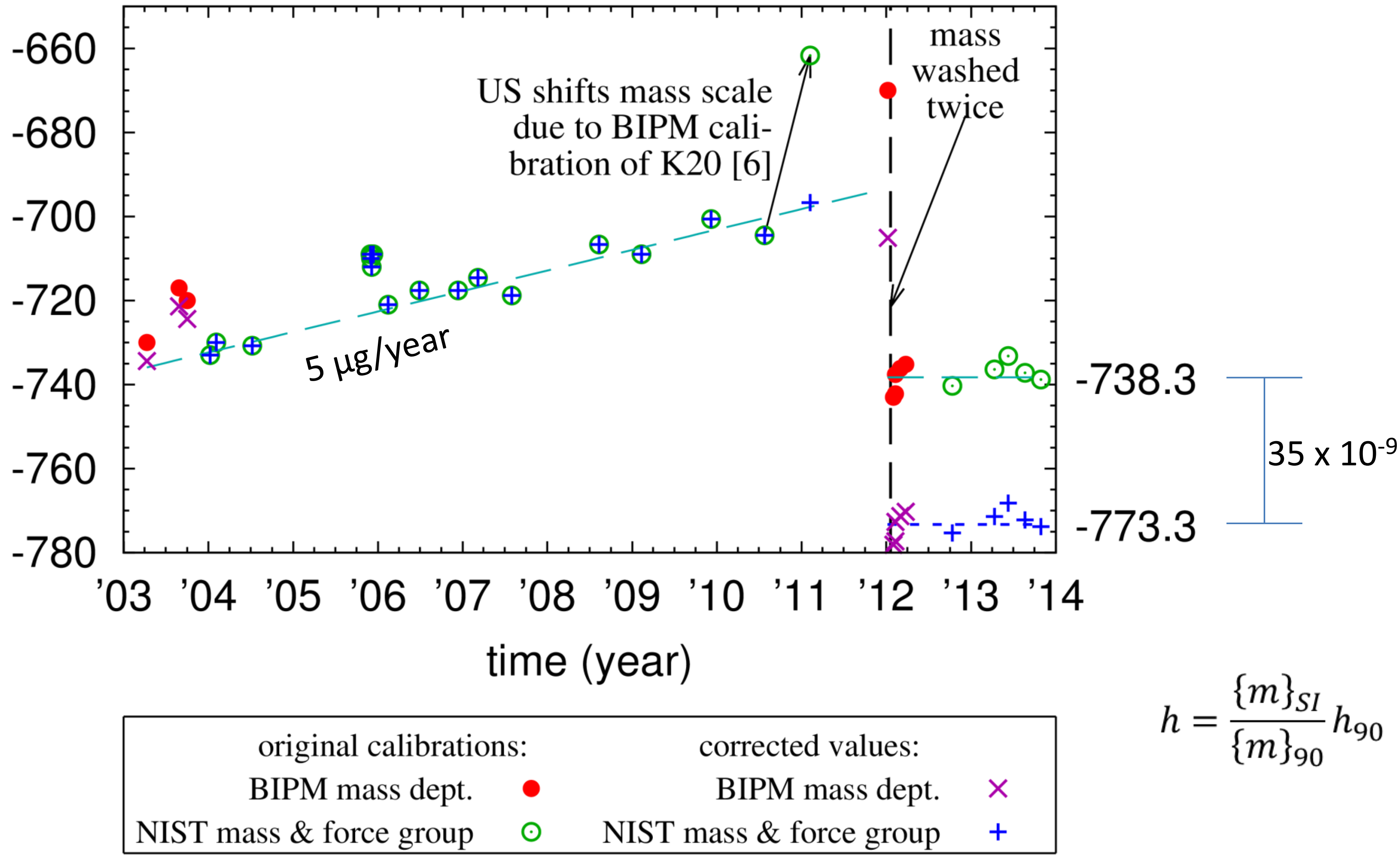
The result at the end of 2013



$$h_{07} = 6.626\,068\,91(24) \times 10^{-34}\ \mathrm{J\,s} \qquad \frac{h_{07}}{h_{90}} = 8(36) \times 10^{-9}$$

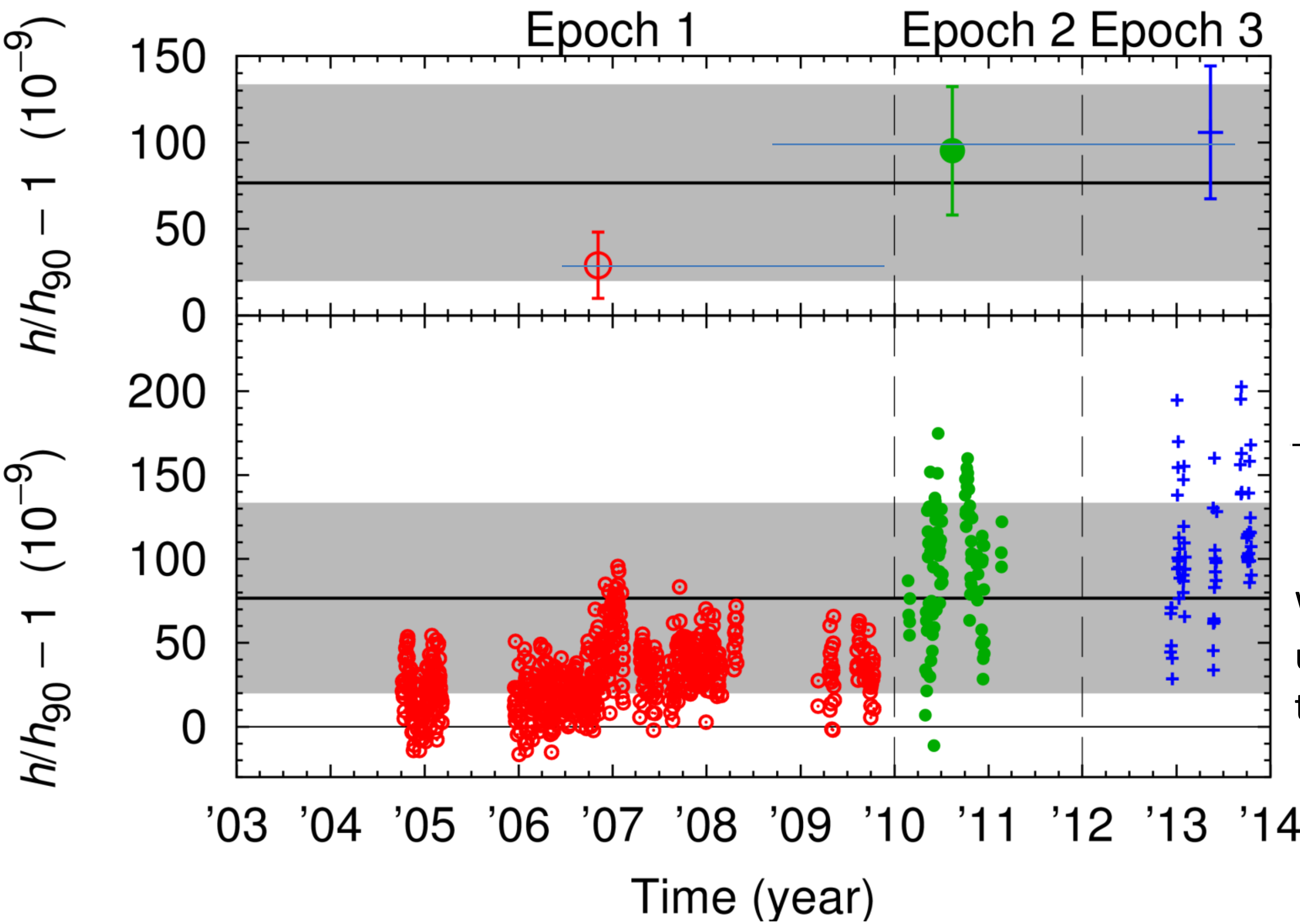
$$h_{14} = 6.626\,069\,79(30) \times 10^{-34}\ \mathrm{J\,s} \qquad \frac{h_{14}}{h_{90}} = 141(45) \times 10^{-9}$$

Calibration history of K85



$$h = \frac{\{m\}_{SI}}{\{m\}_{90}} h_{90}$$

Calibration history of K85



	h/h_{90}-1 (10^{-9})	s_h/h (10^{-9})
1	29	19
2	95	37
3	106	38
m	77	

We add a 35x10^{-9} uncertainty to reflect the shift

National Institute of Standards and Technology
U.S. Department of Commerce

The final NIST-3 number

$$h_{NIST-3} = 6.626\,069\,36(37) \times 10^{-34}\ \mathrm{J\,s}$$

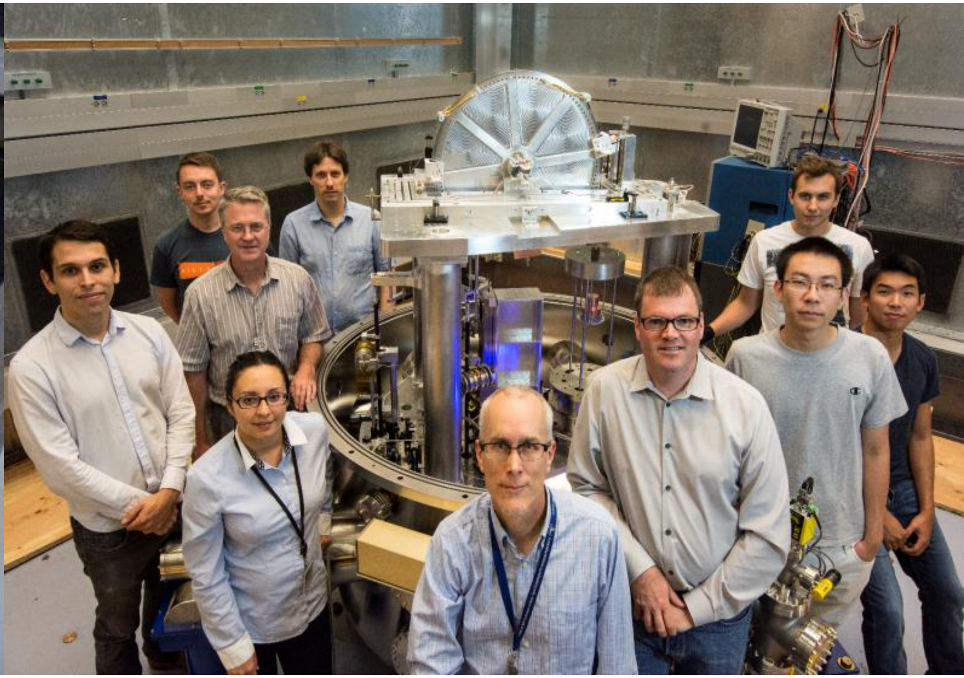
$$\frac{h_{NIST-3}}{h_{90}} = 77(57) \times 10^{-9}$$

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

In the meantime

December 2013

August 2014



NIST-4 is being assembled

NIST-4 status

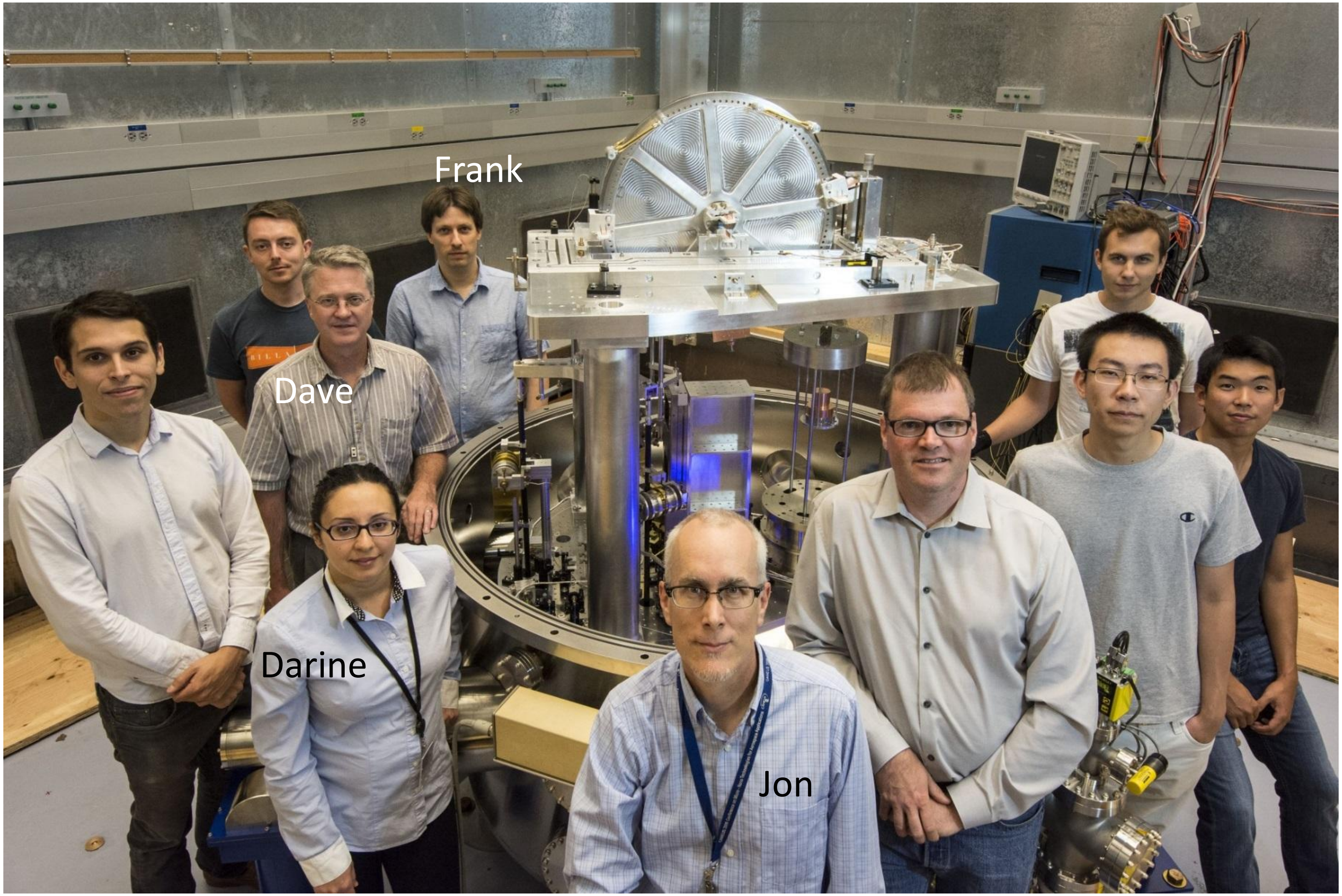
- Preliminary measurements in velocity mode (without PJVS)
- Preliminary measurements in force mode (in air)
- We are working on combining the two modes.
- We hope to have a first measurement of h in the spring of 2015.
- And a more precise value at the end of 2015.

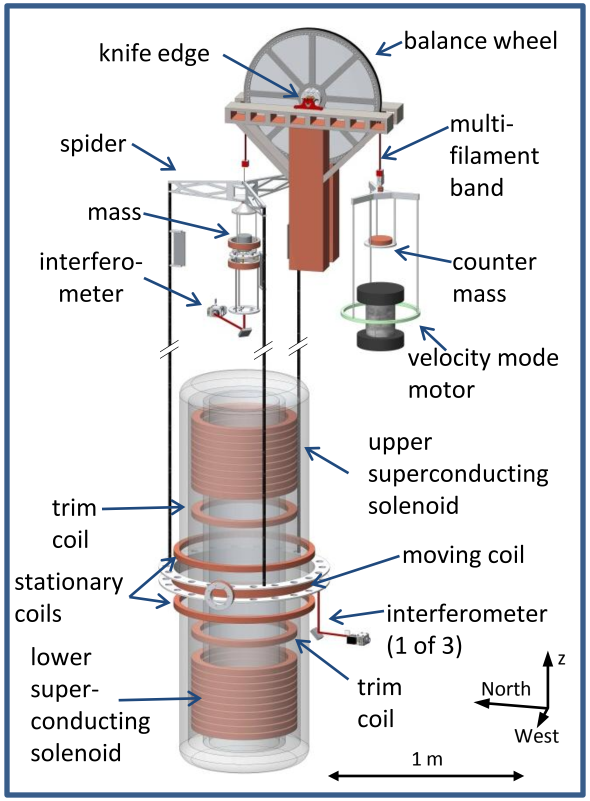
→ Poster

Conclusions

- NIST-3 was used to measure h with K85 from 2003-2013.
- The final relative uncertainty is 57×10^{-9} .
- In 2010 the data shifted by 70×10^{-9} and the statistical noise increased. No single reason for this shift could be identified.
- A relative uncertainty of 35×10^{-9} was added to the uncertainty budget to reflect this shift.
- This is the largest uncertainty.

Thank you for your attention




knife edge
balance wheel
spider
multi-filament band
mass
interfero-meter
counter mass
velocity mode motor
upper superconducting solenoid
trim coil
moving coil
stationary coils
interferometer (1 of 3)
lower super-conducting solenoid
trim coil
z
North
West
1 m